The Geology and Hydrodynamics of the Proposed Low Level Nuclear Waste Repository Site at the Vermont Yankee Nuclear Power Plant, Vernon Vermont

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation **with distinction in Geological Sciences** in the undergraduate colleges of The Ohio State University

by

Thomas Doumaux

The Ohio State University
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Project Adviser: Professor Thomas Naymik, Department of Geological Sciences

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I. Background

The federal Low-Level Radioactive Waste Policy Act of 1980 and its Amendments of 1985 require that all states provide for the disposal of certain low-level radioactive waste (LLRW) generated within their borders. On June 29, 1990, the Vermont legislature established the Vermont Low-Level Radioactive Waste Authority, which is charged with, among other duties, the selection of a site for a disposal facility. Vermont pursued two approaches for the selection of a suitable site for a LLRW disposal facility. The first of these efforts was the evaluation of the Vermont Yankee nuclear power plant site. The second was a statewide screening process to identify at least three potential alternative sites.

The Vermont Low-Level Radioactive Waste Authority hired Battelle, a Columbus based technology company, as the primary contractor. Battelle was charged with organizing and completing the site characterization of the Vermont Yankee site and alternative sites if necessary. This site characterization was the initial study of the proposed site, according to federal, state, and local regulations, and procedures established by Battelle. One of Battelle's goals, and the purpose of this thesis was to help determine if the proposed low-level nuclear waste repository site, to be located on the grounds of the Vermont Yankee nuclear power plant, could pose an environmental threat should accidental releases contaminate the groundwater of the region. These studies will allow the Vermont Waste Authority to make an informed decision about the suitability of the proposed site (see figure 1). The Hydrogeologic Transport group at Battelle had primary responsibility for integrating the hydrogeological characterization activities. To conduct the site characterization, Battelle has hired two main sub-contractors: Hanson Engineers and Wagner, Heindel and Noyes (see figure 2).

In the summer of 1991, I became a part-time employee at Battelle and was offered the unique opportunity to become a part of this project. The Vermont project is a very large and complex project

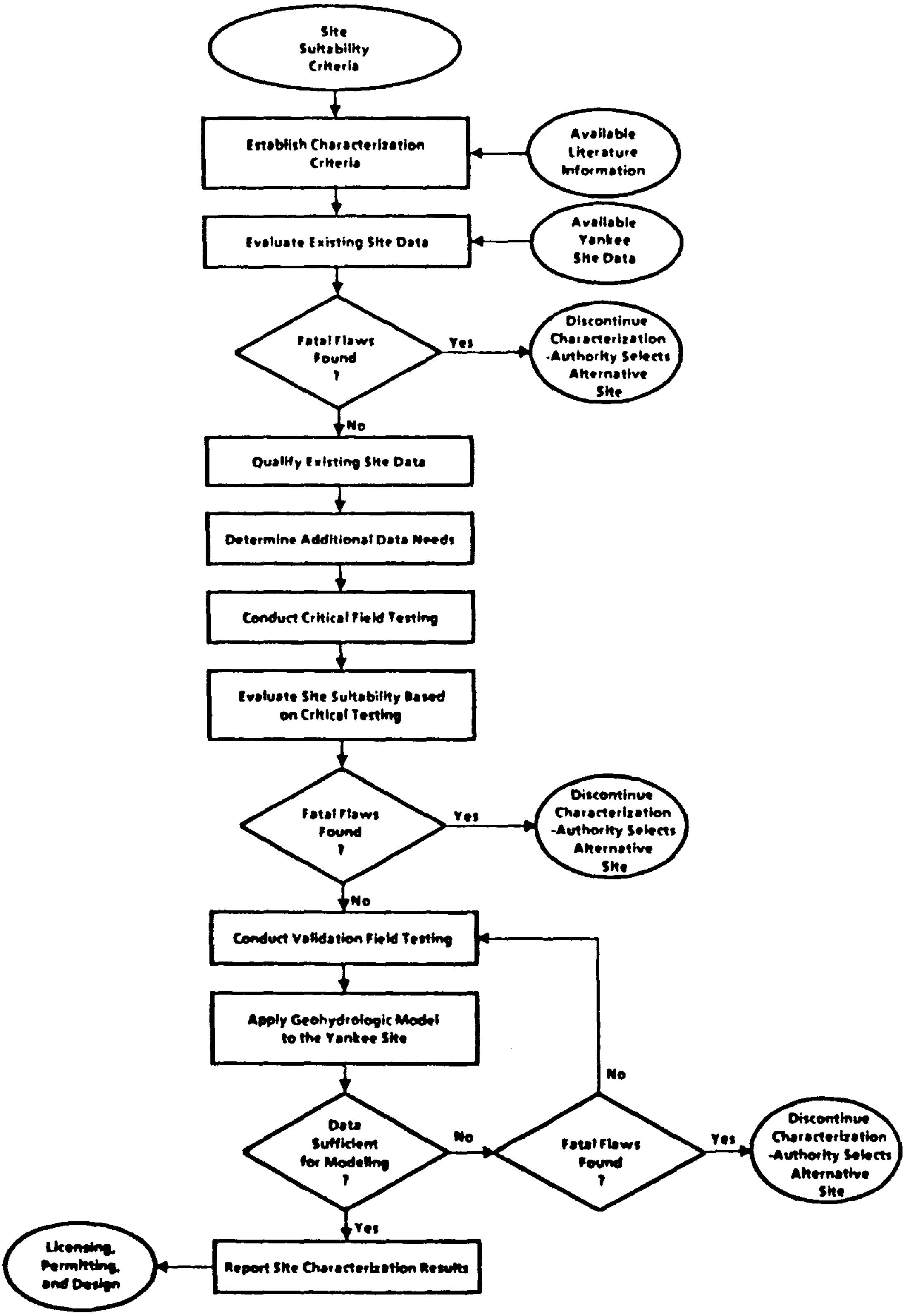


Figure 3-1. The Battelle Site Characterization Process Assures Completeness.

figure 1

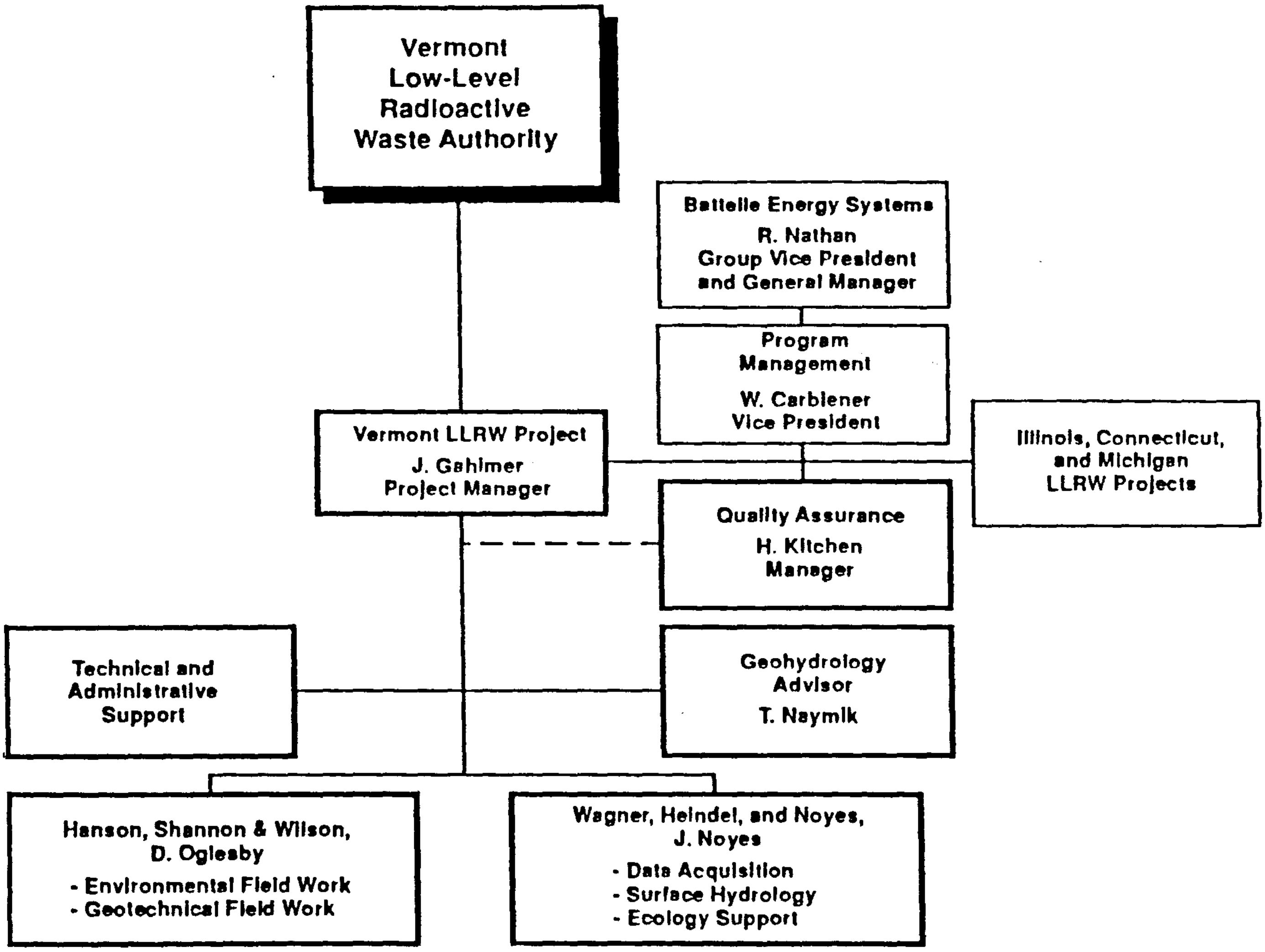


Figure 4-1. Battelle's Vermont LLRW Project Organization.

figure 2

with studies spread between Battelle and its sub-contractors. The sub-contractors mainly conducted field studies and collected data which was sent to Battelle for the Hydrogeologic Transport group to analyze. Battelle used this information to conduct its studies, which included: (1) geography and demography, (2) groundwater hydrology, (3) groundwater conceptual model, (4) groundwater flow modeling (not completed), and (5) groundwater conditions (see figure 3). Though I have worked as a part of a team on the overall Vermont project, I have had independent responsibility to carry out my studies. My studies will contribute to Battelle's larger study of the groundwater hydrology and groundwater conditions of the proposed site.

My thesis has gone beyond what I had been asked to do at Battelle. At Battelle I have studied the existing geology and hydrogeology of the site. For Battelle to fulfill its duties these are the only studies they need to conduct, but rather than leave my thesis at this, I have worked to learn not only what the physical conditions of the site are, but how the geology of Vermont formed. This includes historical mountain building episodes, deformation of the continental crust, metamorphism, folding, doming, repeated glaciation, and recent erosion and deposition. I feel this historical geologic approach will bring an understanding of how and why to the what of the geology and hydrogeology of the site. In order of discussion, my thesis will cover the following: the physiographic divisions of Vermont, the regional geologic setting, the bedrock geology, the glacial history, the surficial geology, the site description and finally, the hydrologic conditions and flow regime.

II. Physiographic Provinces of Vermont

There are six major geomorphic subdivisions of Vermont: the Green Mountains, the Taconic Mountains, the Vermont Valley, the New England Upland (Vermont Piedmont), the Northeast Highlands and the Champlain Lowlands (see figure 4). Since only the Green Mountains and the New

(1)
- Geography and Demography
  - Designation of study area for each technical investigation (NUREG 1199, et al.)
  - Geographic description of area
  - Number and distribution of population
  - Population trends and projections
  - Projected residential, commercial, and residential development
- Geologic and Seismic
  - Geomorphology
  - Stratigraphy
  - Lithology
  - Structural Geology and Tectonics
  - Seismicity
- Geologic Resources
  - Past and Present Resources
  - Mineral Rights and Lease Data
  - Borehole and Well Data
  - Potential Resource Location
  - Resource Quality and Quantity
  - Resource Value
  - Effects of Exploitation
  - Resource Impact
- Hydrologic
  - Surface Water Hydrology
  - Surface Water Inventory
  - Surface Water Use
  - Flood Hazard Analysis
  - (2) Groundwater Hydrology
  - (3) Groundwater Conceptual Model
  - Groundwater Use
  - (4) Groundwater Flow Modeling
- Geotechnical
  - Soil Classification
  - Engineering Properties
  - Engineering Units
  - (5) Groundwater Conditions
  - Engineering Analysis
- Environmental
  - Ecology (terrestrial and aquatic)
  - Water Quality
  - Soils
  - Land Use/Agriculture
  - Acoustics/Noise
  - Background Radioactivity
- Meteorology and Climatology
- Cultural Resources
  - Archeological
  - Architectural
  - Historic
  - Scenic
- Socioeconomics
  - Services
  - Fiscal
  - Employment
  - Transportation Routes/Hazards

Figure 3-3. Categories of Data to be Included in Site Characterization

figure 3

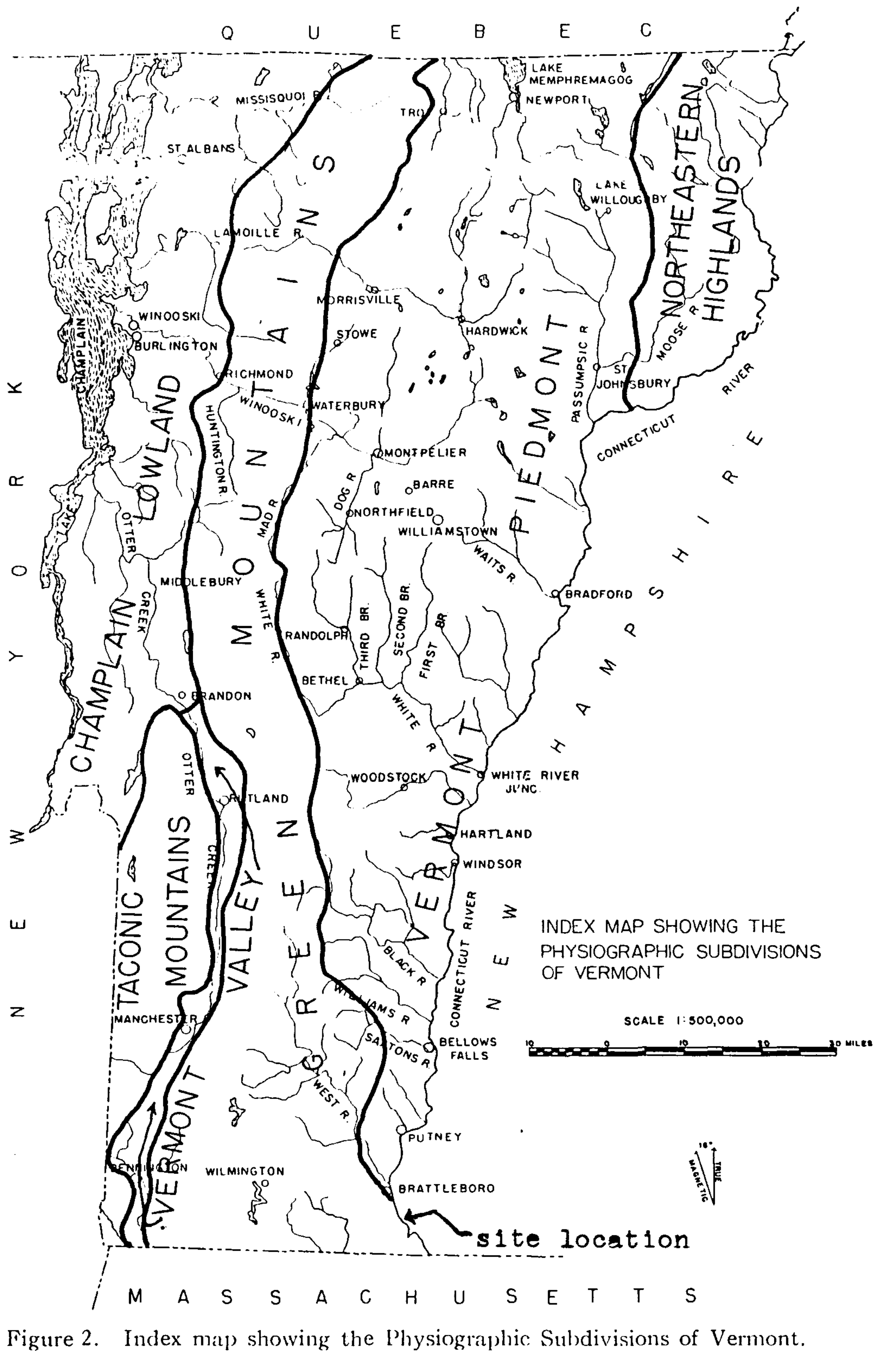


Figure 2. Index map showing the Physiographic Subdivisions of Vermont.

figure 4

England Upland are relevant to the study area, the area technically being in the Green Mountain province but really more closely related to the New England Upland, only these provinces will be discussed.

The Green Mountains cross the state from north to south and form most of the topography of Vermont. The mountains are 21 miles wide at the Canadian border and 36 miles wide at the Massachusetts border. Summit elevations average 2,000 feet but there are five peaks over 4,000 feet. The mountains rise abruptly from the lowlands on the west and the rolling plateau to the east. The mountains are rugged with sharp crests and steep slopes.

The New England Upland extends to eastern Vermont and covers most of the state east of the Green Mountains. The Vermont Piedmont is that portion of the upland within the boundaries of Vermont. The surface is a plateau that has been dissected by streams and subdued by glaciation. The topography, though subdued in relation to the Green Mountains, is undulating to rough because of numerous steep-sided valleys. Several small mountains rise above the plateau, as do plutons, both acidic (silicic) and basic (mafic), that intrude the metasediments. The Connecticut River south of St. Johnsbury is entrenched into the complex crystalline rock of the upland. The valley is narrow in some sections and a few miles wide in others, but in all sections the valley walls are abrupt and steep.

III. Regional Geologic Setting/Bedrock Geology

So that the reader may understand the relevance of this discussion of the bedrock geology, the exact location of the Vermont Yankee Site will be noted here. The site is located in the extreme southeast corner of the Brattleboro quadrangle just north of the Massachusetts border. It is located on the stream bank on the western side of the Connecticut River just north of a distinctive ox-bow like bend in the Connecticut River. The site is located on the Vernon Dome on western limb of the

Bronson Hill anticlinorium. The site is underlain by the Oliverian Plutonic Series. The highlands to the west consist of the Littleton Formation, the Clough Formation, and the Ammonoosuc Volcanics.

The Brattleboro 15 minute quadrangle covers approximately 202 square miles in Windham County in southeastern Vermont and 23 square miles in Cheshire County in southwestern New Hampshire. The quadrangle lies between north latitudes 43°00' and 42°45'; west longitudes 72°30' and 72°45' (see figure 5). The Brattleboro quadrangle lies along the western margin of the New England Upland section and the eastern margin of the Green Mountain section of the New England Physiographic province. The maximum topographic relief is 1,840 feet. The high point is 2020 feet and the low point 180 feet above standard mean sea level. The local topographic relief averages 500-1,000 feet.

The quadrangle consists of three major structural features: the Bronson Hill anticlinorium, the Connecticut River-Gaspe synclinorium (locally named the Brattleboro Syncline), and the Green Mountain anticlinorium (see figures 6,7,7A). The eastern portion of the Brattleboro quadrangle is on the west limb of the Bronson Hill anticlinorium. The central and western portions of the Brattleboro quadrangle lie in the Connecticut River-Gaspe synclinorium and on the eastern limb of the Green Mountain anticlinorium. The Connecticut River-Gaspe synclinorium consists of Siluro-Devonian rocks, disrupted by the mantled gneiss domes of the Green Mountain anticlinorium. The Bronson Hill anticlinorium is a complex series of domes with granitic gneiss cores. The Vernon dome is one of 20 such structures in an anticlinorium which stretches from Berlin New Hampshire to Long Island Sound. Lower Paleozoic metasediments and metavolcanics in the Eastern Sequence of the Brattleboro region, occur as both mantling strata to these domes and in larger recumbent folds which pre-date doming. The axial surfaces of these folds have been arched by the rising of the domes.

The formations which make up the Brattleboro syncline occur at a relatively low metamorphic

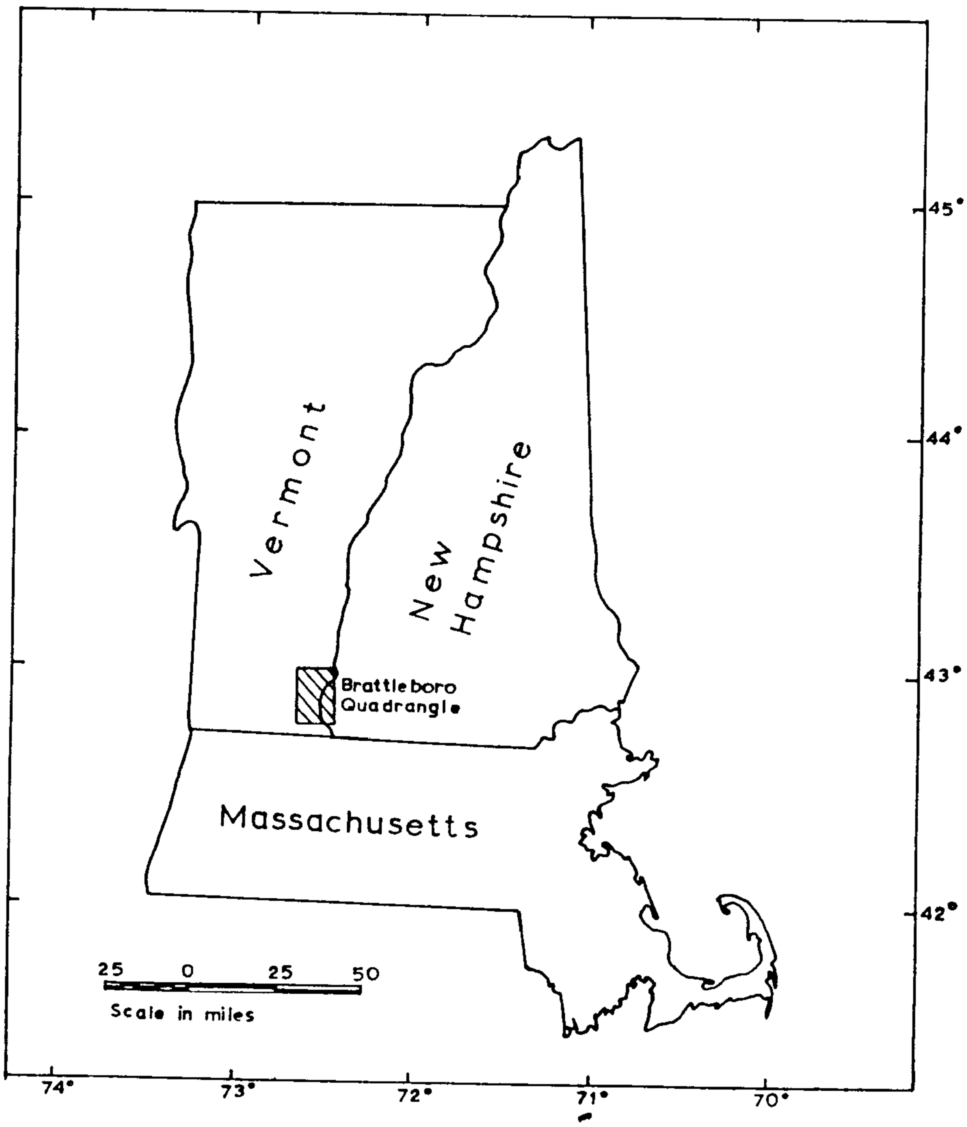


Figure 1-1. Location of the Brattleboro Quadrangle.

figure 5

Figure 1-2. Map showing the regional geologic features and the location of the Brattleboro quadrangle. The contact between the Ordovician and older rocks to the west and the Silurian-Devonian rocks to the east is shown for Vermont and Massachusetts west of the Connecticut River. East of the river, the Paleozoic metasedimentary rocks are undifferentiated. Modified from Hepburn (1975), Doll et al. (1961), Thompson et al. (1968), and Billings (1956).

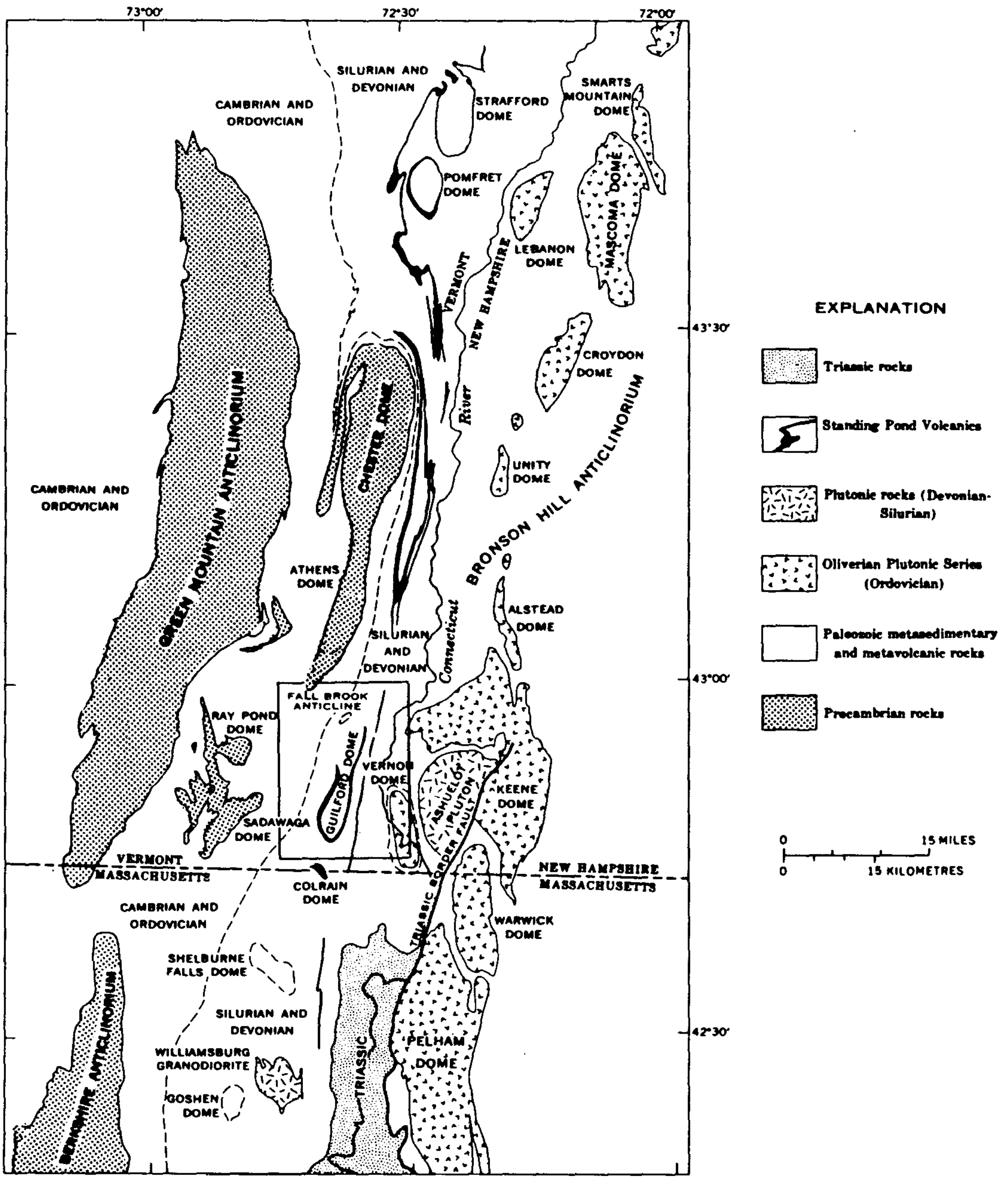


figure 6

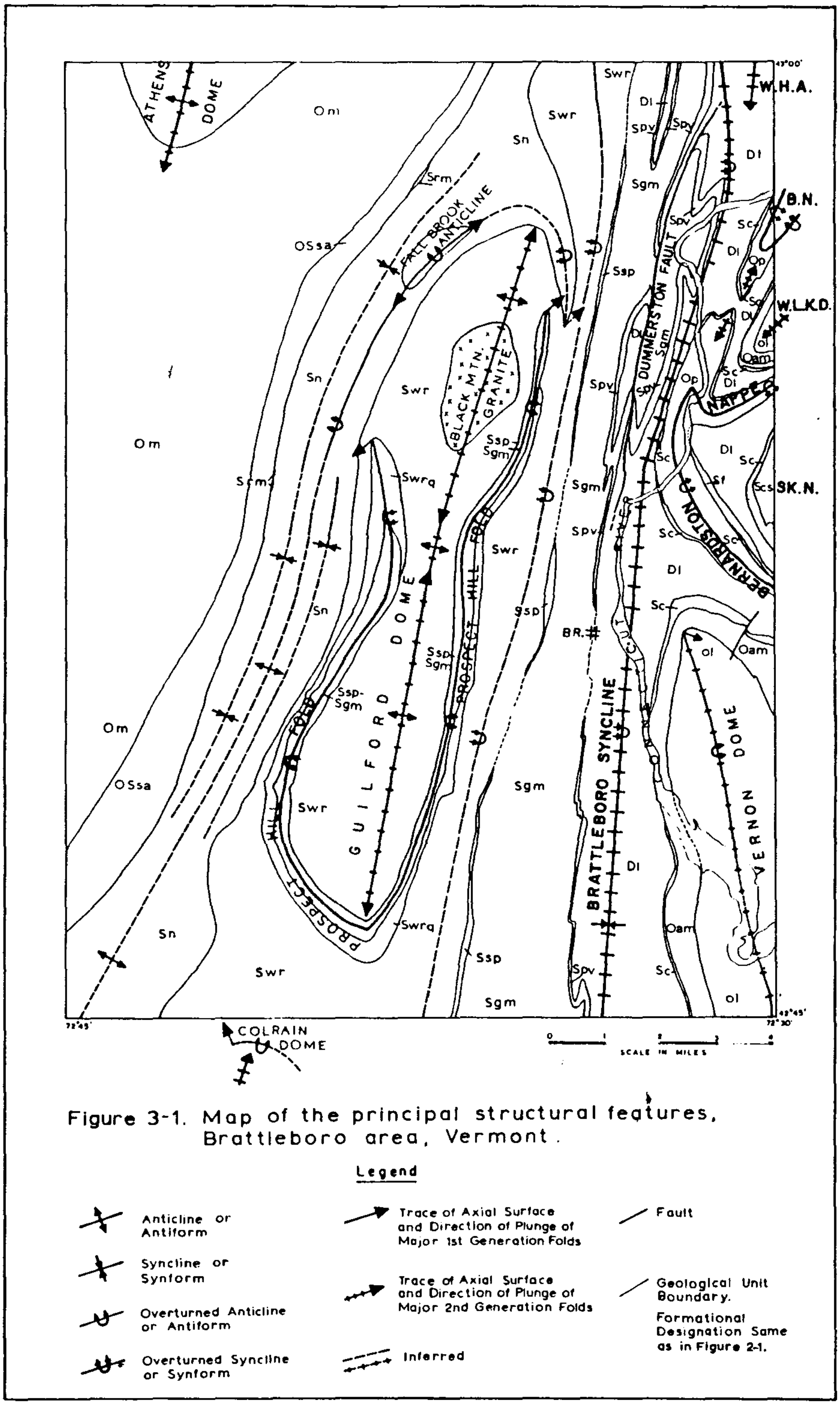


Figure 3-1. Map of the principal structural features in the Brattleboro quadrangle. Abreviations: BR. # = location of Brattleboro center, W.L.K.D. = Westmoreland lobe of Keene dome, B.N. = Bernardston Nappe, W.H.A. = Wellington Hill Anticline. The shading is on both limbs of the Standing Pond Volcanics and the Gile Mt. Fm. in the core of the Prospect Hill recumbent fold. For more detail on the eastern portion of the area, see Figure 6-1. Formational abbreviations are the same as Figure 2-1 or Plate I.

"EASTERN SEQUENCE"

WEST FLANK BRONSON HILL ANTICLINORIUM
EAST FLANK CONNECTICUT RIVER—GASPÉ SYNCLINORIUM

Dl | Dlc

LITTLETON FORMATION

Dl: Gray to dark gray slate, phyllite and mica schist with interbedded quartzite; biotite, garnet and staurolite porphyroblasts common at the appropriate metamorphic grades.
Dlc: Polymict conglomerate with a fine-grained slate to phyllitic matrix; vein quartz and slate pebbles abundant to scarce.

Scs | Sc

CLOUGH QUARTZITE

Sc: White to light-gray quartz-pebble and quartzite-pebble conglomerate in a quartzite and quartz mica schist matrix; white quartzite; muscovite schist.

Scs: Gray mica schist.

Oam

AMMONOOSUC VOLCANICS

Oam: Light-gray, well-foliated quartz-feldspar-biotite gneiss with thick interbeds of amphibolite more abundant in the lower part of the formation; minor sulfidic muscovite-quartz schist near top; scattered lenses of breccia.

PLUTONIC ROCKS

MIDDLE DEVONIAN

nhg

NEW HAMPSHIRE PLUTONIC SERIES

nhg: Medium- to coarse-grained, light-gray, to gray, granite, granodiorite and quartz diorite; some bodies weakly to moderately foliated; aplite.

ORDOVICIAN

ol

OLIVERIAN PLUTONIC SERIES

ol: Medium- to coarse-grained, gray to pink, sub-porphyritic, granodiorite, quartz diorite and quartz monzonite gneiss, strongly to weakly foliated.

um

ULTRAMAFIC ROCKS

um: Massive, dark green serpentinite, gray pitted talc-carbonate, local actinolite alteration at contact with country rock.

MAP SYMBOLS

CONTACTS

Good Control

Fair Control

Inferred

D
High-angle fault (D on downthrown side, dashes and dots as above)

Thicknesses of particularly thin units have been slightly exaggerated (locally) so that these units may be shown on the map at this scale.

STRUCTURAL SYMBOLS

56
Strike and dip of bedding (upright or direction of top unknown)

34
Strike and dip of overturned bedding

67
Strike and dip of foliation

Strike and dip of vertical foliation

METAMORPHIC ISOGRADS

Bt
Isograd, accurately or approximately located, hachures on side of higher metamorphic grade: Bt = Biotite, Gt = Garnet, St = Staurolite, St-Ky = Staurolite-Kyanite. Ch = rocks in the Chlorite Zone.

CONTACT METAMORPHOSED ROCKS

Rocks altered by contact metamorphism in aureole surrounding the Black Mountain Granite, numerous dikes and sills of granite in the country rock as main body is approached.

Larger granitic dikes or sills

GEOLOGY BY

J. C. HEPBURN, N. J. TRASK, J. L. ROSENFELD, J. B. THOMPSON, JR.

GEOLOGIC MAP OF THE BRATTLEBORO QUADRANGLE VERMONT-NEW HAMPSHIRE

VERMONT GEOLOGICAL SURVEY

Charles A. Ratté, State Geologist
(Bulletin No. 32)

grade within the syncline. The syncline strikes N.10°E. Both limbs and the axial surface are vertical or dip steeply to the east. The axis is essentially horizontal, and is located in the Littleton Formation east of the "Chicken Yard line" and west of the domes and nappes of the Bronson Hill anticlinorium.

The eastern flank of the Green Mountain anticlinorium consists of a topping sequence of metamorphosed Ordovician sediments and volcanics. The sequence is interrupted by four mantled gneiss domes with Precambrian rock cores. These domes are part of a belt of domes along or just west of the axial region of the Connecticut River-Gaspe synclinorium, which extends southwards from east central Vermont to Connecticut. These domes are analogous to but much more widely spaced than the domes of the Bronson Hill anticlinorium. Some domes have only Paleozoic metamorphic rocks exposed in their central portions in addition to those domes with Precambrian cores. The Guilford Dome with the Silurian rocks exposed in its central portion is in the central area of quadrangle. Large recumbent folds are also present in the strata mantling the domes of this western belt. The axial surfaces of these folds are arched by the domes (see figures 8,9).

Secondary foliation is well developed in all metasediments and metavolcanic rocks. Where bedding or compositional layering is present, the major secondary foliation is generally parallel or subparallel to it. Schistosity is the most common secondary foliation, but slip cleavage and fracture cleavage are also present. Lineations and minor folds have also been noted.

Metamorphic highs to the staurolite-kyanite zone are associated with the Chester, Athens, Colrain and Guilford domes. The grade of metamorphism decreases to the chlorite zone in a narrow band along the Connecticut River. This belt is part of a regional metamorphic low that extends northwards from the northern limit of the Triassic basins near Greenfield Massachusetts, to northeastern Vermont along or near the Connecticut River Valley. Eastward from this belt, metamorphic grades increase sharply to highs in the sillimanite and sillimanite - K-spar zone of the Bronson Hill anticlinorium.

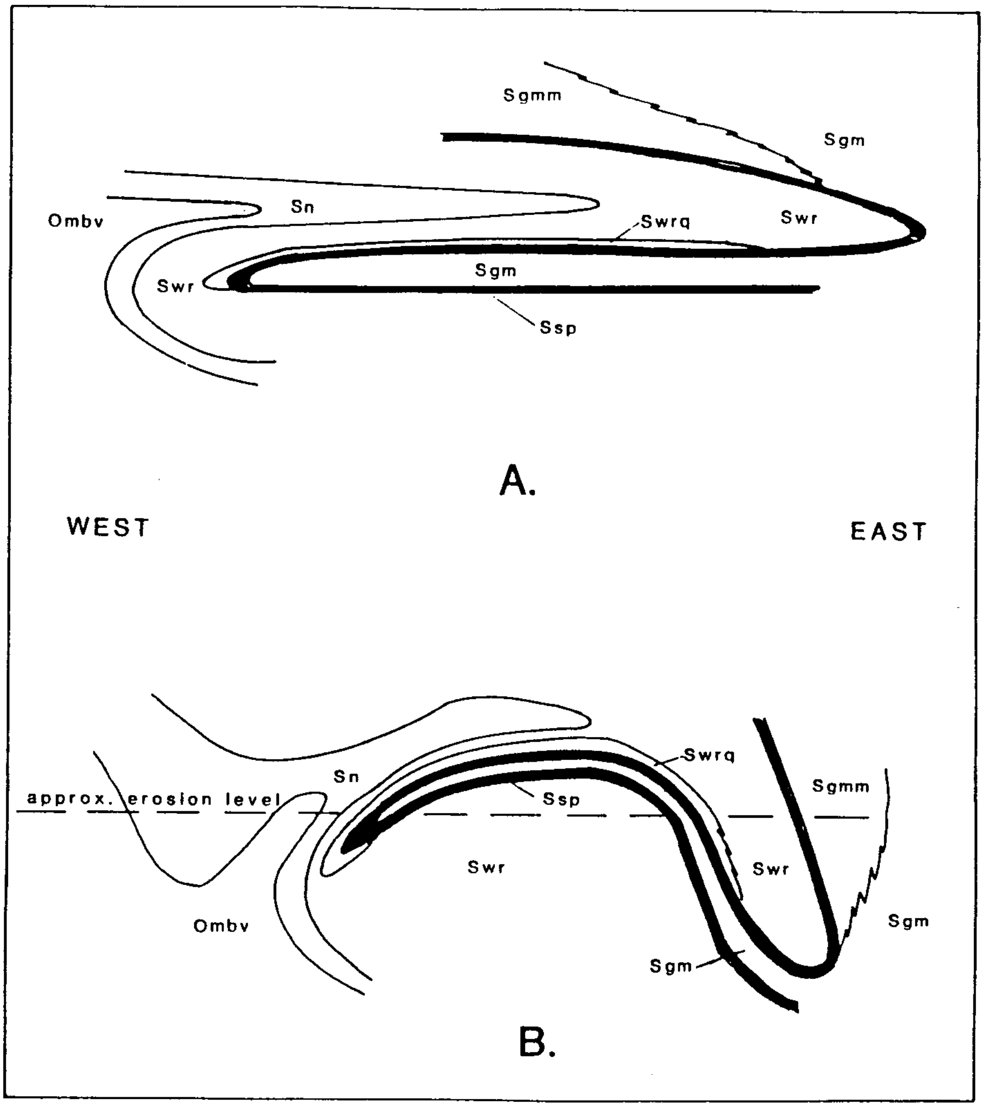


Figure 3-21. Schematic cross sections showing the evolution of the structural features in the two major stages of deformation in the Guilford dome area. The Standing Pond Volcanics are shown in black. (A) The Prospect Hill fold at the end of the first major stage of deformation, before the rise of the Guilford dome. (B) Prospect Hill fold following the second major stage of deformation, after the rise of the Guilford dome. The horizontal line represents the erosion surface. Formations: Sgm = Gile Mt. Fm.; Sgmm = marble mbr., Gile Mt., Fm.; Swr = Waits River Fm.; Swrq = quartzitic mbr., Waits River Fm.; Sn = Northfield Fm.; Ssp = Standing Pond Volc. (in black); Ombv = Barnard Volc. Mbr., Missisquoi Fm. Modified in part from Hepburn, 1975.

figure 8

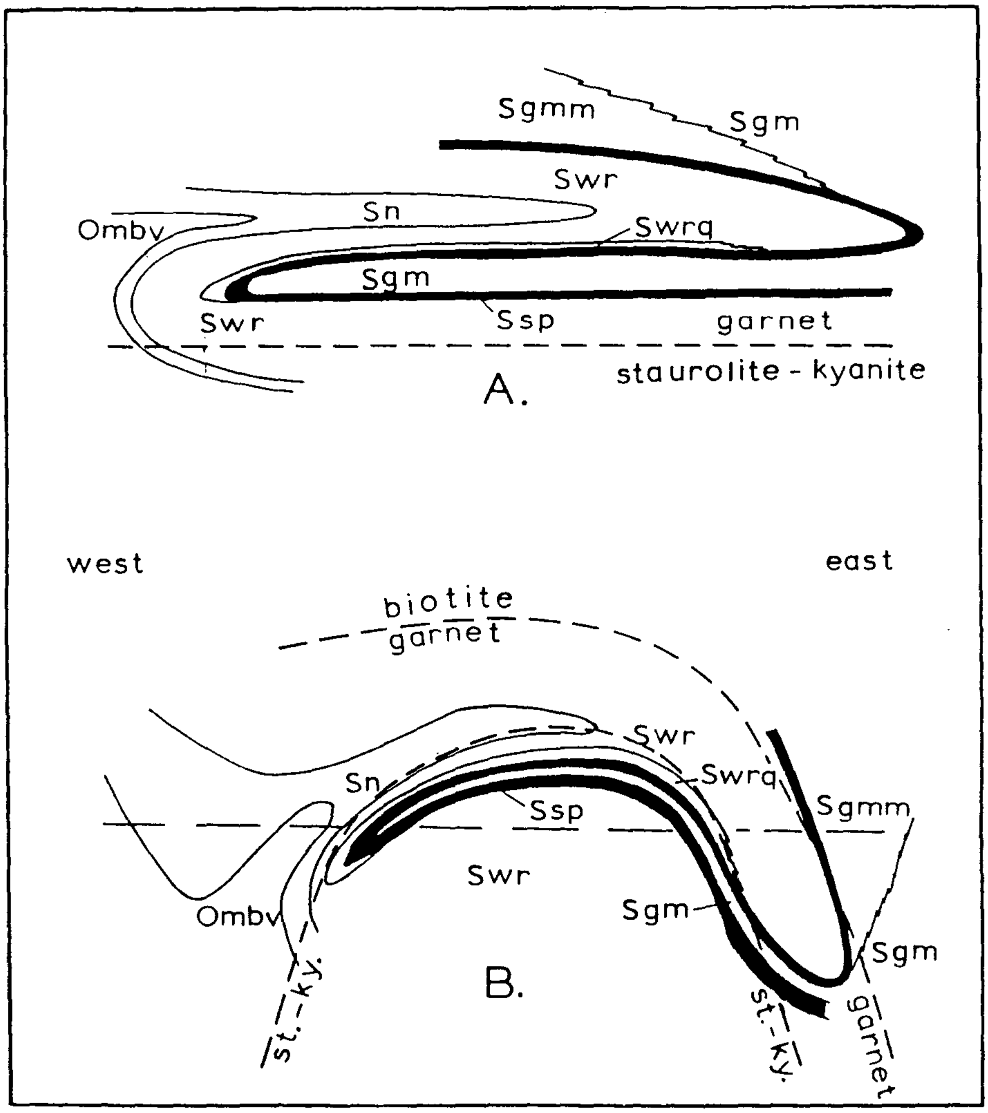


Figure 4-8. Schematic cross sections showing the evolution of the structural features in the two major stages of deformation in the Guilford dome area. The Standing Pond Volcanics is shown in black. (A) Prospect Hill fold at the end of the first major stage of deformation, before the rise of the Guilford dome. The dashed line represents a hypothetical staurolite or kyanite isograd. (B) Prospect Hill fold following the second major stage of deformation, after the rise of the dome. Horizontal line represents the present erosion surface. The dashed lines show the assumed present distribution of isogrades. Modified after Hepburn, 1975. Formations: Sgm = Gile Mt.; Sgmm = Gile Mt., marble mbr.; Ssp = Standing Pond Volc.; Swr = Waits River Fm.; Swrq = Waits River Fm., quartzitic mbr.; Sn= Northfield Fm.; Ombv, Missisquoi Fm., Barnard Volc. Mbr.

figure 9

The domes may have been formed by the near vertical diapiric upward movement of the core rocks, possibly the result of the lower specific gravities of these rocks. Doming followed emplacement of recumbent folds as is evidenced by the outcrop pattern of the Prospect Hill fold around the southern end of the Guilford dome. The metamorphic high centered on the Guilford dome also indicates these rocks were hotter than the surrounding rocks presently exposed at the surface.

A. Stratigraphy

The stratigraphy of the region is divided into two sequences: the Eastern Sequence and the Western Sequence (see figure 10). The Western Sequence includes the east limb of the Green Mountain anticlinorium and the western flank of the Connecticut River-Gaspe synclinorium (that is, west of the outcrop belt of the Littleton Formation). The Eastern Sequence includes the Bronson Hill anticlinorium and those areas east of the Putney Volcanics-Littleton Formation contact. The two sequences are roughly contemporaneous but since each has a distinct stratigraphy and correlation is difficult, the sequences remain separate.

Since all of the Vermont Yankee site and relevant topographic highs to the west of the site are in the Eastern Sequence, the stratigraphy of the Western Sequence will not be discussed. The Eastern Sequence consists of the the Ordovician Ammonoosuc Volcanics, the Partridge Formation, the Silurian Clough and Fitch Formations and the Devonian Littleton Formation. The grade of regional metamorphism increases progressively from west to east across the Eastern Sequence from the chlorite zone to the staurolite zone. The Littleton Formation is in all metamorphic zones. The Partridge and Clough Formations are in the garnet and staurolite zones. The Ammonoosuc Volcanics and most of the Fitch Formation are in the staurolite zone.

The Ordovician Ammonoosuc Volcanics

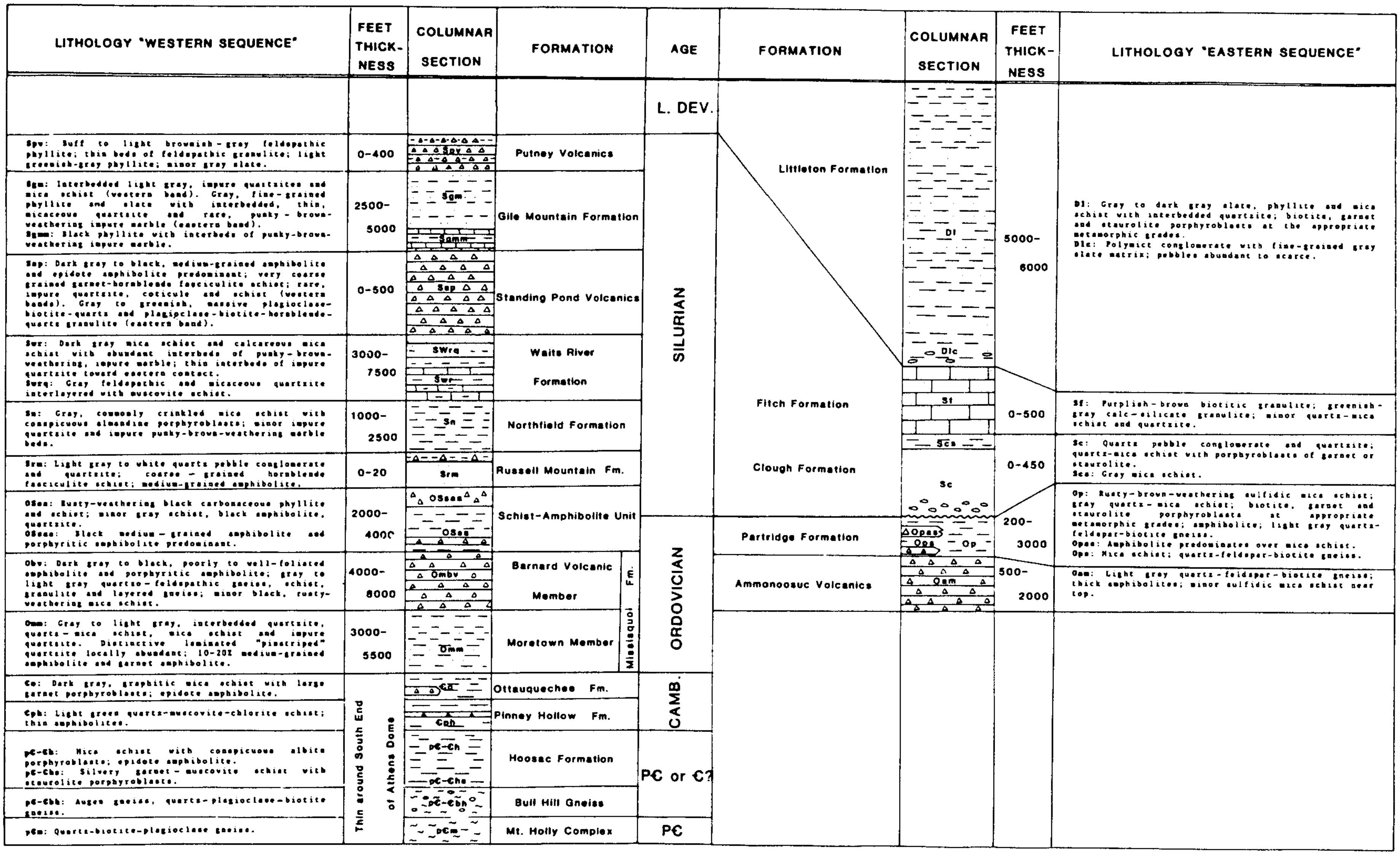


Figure 2-1. Stratigraphic column for the Brattleboro quadrangle, showing correlations between the Western and Eastern Sequences.

The Ammonoosuc volcanics are more resistant than the structurally underlying plutonic rocks of the Oliverian Series. An exact contact with the Oliverian Plutonic Series is not found in the area, and there may be sills of Oliverian Plutonics in the Ammonoosuc Volcanics. Two-thirds of the formation consists of quartz-feldspar-biotite-gneisses and one-third consists of amphibolite. The two are interlayered on all scales and this probably reflects original volcanic stratification. The quartz-feldspar-biotite-gneiss is well foliated, and light gray in color. Medium-fine grained quartz and plagioclase feldspar are the principal constituents of the gneiss, and biotite accounts for 1-10%. The amphibolite is medium-coarse grained and includes schistose and non-foliated types.

The Ordovician Partridge Formation

The Partridge Formation is a varied sequence of schists, amphibolites, quartz-feldspar-biotite-gneiss and granulite. Quartz mica schist accounts for about 70%, amphibolite 20%, quartz-feldspar-biotite-gneiss and granulite 10%, and conglomerate and calcsilicate granulites < 1% of the formation. The formation consists of two poorly defined subunits. The first is a schist subunit which consists of mica schist and is interbedded with amphibolite and quartz-feldspar-biotite-gneiss. The second is an amphibolite and schist subunit which consists of interbeds of amphibolite and schist with slightly more amphibolite than schist. Mica schists are gray. About 60% of the schists are sulfidic. These sulfidic schists are fine grained with a dense, poorly foliated appearance in the garnet zone. Medium to coarse grained amphibolites are interbedded throughout the Partridge Formation, but are most common in the amphibolite-schist subunit. Foliation is absent in the central portions of the thicker, coarse grained amphibolites, but is present in thinner, medium grained amphibolites and on the margins of larger bodies. The amphibolites are gray to dark greenish gray in color. Fine-medium grained quartz-feldspar-biotite-gneiss and granulite are present as scattered interbeds within both subunits. These rocks are light to dark gray. The gneiss is well foliated. A few thin beds of fine grained, dense, gray, calc-silicate granulites are scattered throughout the formation.

The Silurian Clough Formation

The Clough Formation, in the Brattleboro area, consists of two-thirds quartz-pebble conglomerate and one-third quartzite with minor amounts of gray mica schist. This formation is part of the mantling sequences of the Vernon dome. Where the quartzite contains thick beds of conglomerate it is light-gray to white. Where the quartzite has no or thin beds of conglomerate it is light gray to rust color. The conglomerate has pebbles which are flattened and elongated in the plane of foliation. The pebbles are mostly coarse grained quartz or fine grained quartzite. In outcrops with large overlapping pebbles, the matrix is less than 10% of the rock. In other areas a matrix of medium grained quartzite makes up as much as 50% of the rock. Locally, a matrix of mica schist grades along strike to the quartzite matrix.

The Silurian Fitch Formation

The Fitch Formation consists of interbedded fine-medium grained calc-silicate granulites, granulitic schists and mica schists. Many of the granulites and granulitic schists weather to a distinctive purplish brown color. In general, the Fitch Formation is more resistant than the Littleton and Partridge Formations and less resistant than the Clough Formation. Laminae and very thin beds commonly contain concentrations of actinolite, diopside and calcite. Thicker beds usually consist of quartz-biotite granulite, granulitic schist and mica schist. Thin light gray beds of quartzite are locally present. The purplish-brown quartz-biotite granulites and granulitic schists of the Fitch Formation have fair to good foliation. Quartz and biotite are present in all granulites and granulitic schists. Calcite, actinolite, clinozoisite, plagioclase and garnet are the principal remaining constituents and are present in a wide range of proportions. Beds rich in calc-silicate minerals weather to a light gray and are greenish gray on fresh surfaces.

The Devonian Littleton Formation

The Littleton Formation is a relatively thick and dominantly pelitic and quartzose unit. The formation consists mostly of interbedded quartzite and metamorphosed argillaceous rocks with a few scattered lenses of conglomerate at its base. The pelitic rocks grade from slate to phyllite schist. Outcrops are dominantly medium to dark gray. The conglomerate is thin and discontinuous. Somewhat flattened and elongated pebbles of quartz and slate are in a phyllite matrix. A dark gray-black phyllite makes up most of the Littleton Formation in the chlorite-garnet metamorphic zones. Interbedded quartzite and quartzose laminae are present in about half of the outcrops. Fine grained quartz and muscovite are the principal constituents of all slates, phyllites and quartzites in these low grade zones. In the staurolite zone, schist, quartzose schist and quartzite are dominant. These rocks are gray weathered and dark gray-black fresh. Schists grade from fine to coarse grained and consist of quartz, muscovite and biotite. Medium grained quartzites form thin to thick interbeds within larger bodies of schist.

Intrusive Igneous Rocks

There are two important series of igneous rocks: the Oliverian Plutonic Series and the New Hampshire Plutonic Series. Gneisses of the Oliverian Plutonic Series form the cores of domes in the Bronson Hill anticlinorium. In the Vernon dome, the Oliverian Plutonic Series consists of quartz diorite gneiss. The gneisses are light gray to grayish pink, medium grained, sub-porphyritic with hypidiomorphic to granoblastic texture. Foliation in the Oliverian Plutonic Series is best developed around the margins of the gneiss domes. Layers of quartz diorite gneiss as much as 100 feet thick alternate with beds typical of the Ammonoosuc Volcanics at the contact between the two units in the Vernon dome.

The New Hampshire Plutonic Series consists of a number of small, late orogenic to post-orogenic granitic bodies, including small bodies of aplite, granodiorite and quartz diorite. Both concordant and discordant contacts have been observed. The granodiorites are light-medium gray and generally medium grained. One-third are foliated and two-thirds are massive. The well foliated granodiorites have undergone intense deformation. The aplites are white colored, medium grained, muscovite rich rocks with a granitic composition and an aplitic texture.

B. Structure of the Eastern Sequence

The geology of eastern Brattleboro is closer to that of western New Hampshire than the rest of Vermont. The dominant feature is the Bronson Hill anticlinorium, a series of gneiss domes in a more or less en echelon array. Most of the gneiss domes lie in a zone about 20 miles wide just east of the Connecticut River in western New Hampshire. Domes of the Bronson Hill anticlinorium extend southward through central Massachusetts and Connecticut to Long Island Sound east of New Haven.

The gneiss domes are the dominate feature of the Bronson Hill anticlinorium, but represent a relatively late stage in its structural evolution, and were preceded by a series of fold nappes having hinge to hinge displacements as much as 15 miles. Two of the major nappes are the Bernardston and Skitchewaug nappes. The axial surfaces of both nappes were strongly deformed by the later rise of gneiss domes. Subsequent tectonic events include an east-side-north displacement shown by the steeply plunging folds at and near the boundary between the rocks of the eastern and western sequences (the "chicken yard line") and post-metamorphic high angle faulting believed associated with the Mesozoic rift systems of the Connecticut Valley.

The Vernon Dome

The core gneisses of the Vernon dome and the rocks of its western and northern mantle outcrop in the southeast corner of the Brattleboro quadrangle. The core gneisses are of the Oliverian Plutonic Series. The Ammonoosuc, Clough, and Littleton Formations form the surrounding mantle (see figure 11A). The bedding in the mantling strata along the west side of the dome dips steeply east (see figure 11B). Minor folds and cobble elongations along the west side of the dome show gentle southwards plunges near the south of the Brattleboro area. These pass through the horizontal and plunge northward and eventually northeastward as the north end of the dome is approached. The Vernon Dome is a tongue-like body protruding upwards toward the west-northwest (see figure 11C).

The Bernardston Nappe

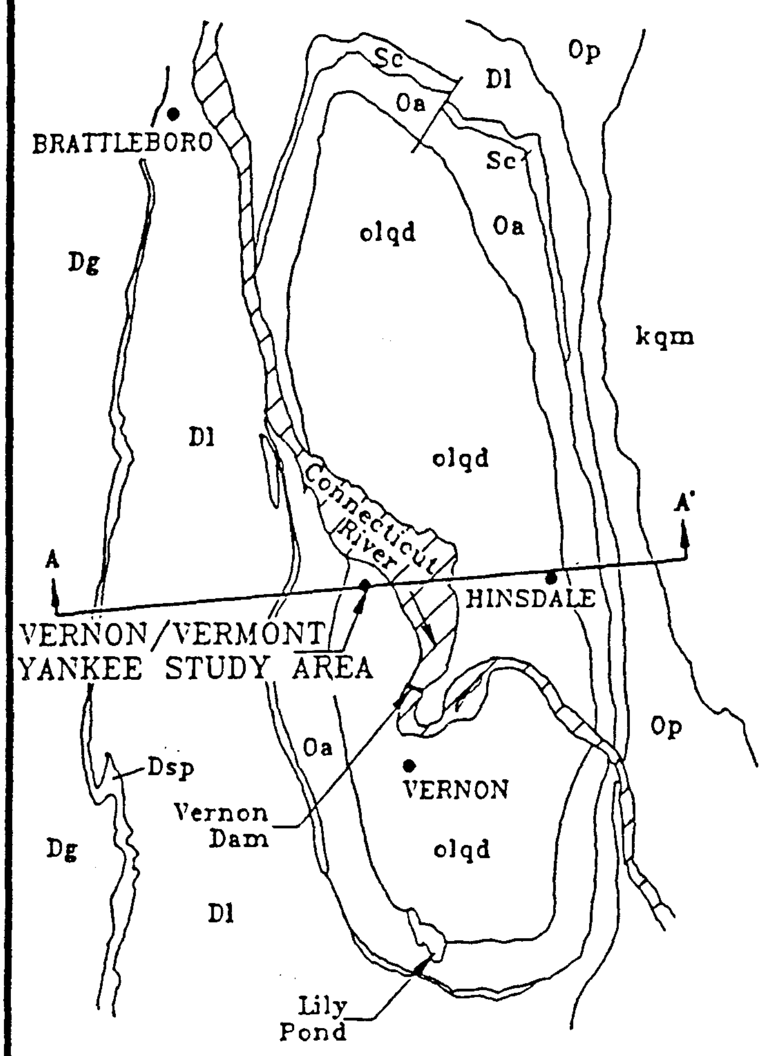
Most exposures of the Partridge Formation in the Brattleboro area lie in the core of the Bernardston Nappe. The sulfidic schists of the Partridge Formation are separated in the inverted limb of the nappe from the schists of the structurally underlying Littleton Formation by a discontinuous band of quartzite and conglomerate of the Clough Formation. Minor exposures of calc-silicate granulite of the Fitch Formation occur at some localities between the Clough and Littleton Formations. The axial surface of the Bernardston nappe and the axial surface of the syncline separating the nappe from the relatively autochthonous gneiss domes have been strongly refolded, both by the rise of the domes and by subsequent events.

The Skitchewaug Nappe

The axial surface of the syncline separating the Bernardston nappe from the structurally higher Skitchewaug nappe, lies in a belt of the Littleton Formation. Only a small portion of the inverted limb of the Skitchewaug nappe is exposed in the Brattleboro area. Rocks of the Fitch and Clough Formations are also believed to make up the nappe.

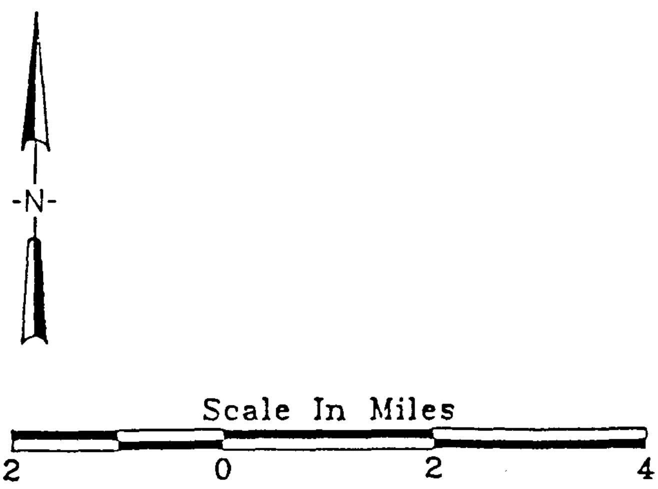
The Chicken Yard Line

The Chicken Yard Line is the boundary between the rocks of the eastern and western sequences



kqm	Kinsman Quartz Monzonite
olqd	Oliverian Plutonic Series Granodiorite, Quartz Diorite and Quartz Monzonite Gneiss
Dg	Gile Mountain Formation Phyllite and Quartzite
Dl	Littleton Formation Slate, Phyllite and Mica Schist. Includes Granodiorite
Dsp	Standing Pond Volcanics Amphibolite and Granulite
Sl	Fitch Formation Granulite and Granulitic Schist
Sc	Clough Quartzite
Op	Partridge Formation
Oa	Ammonoosuc Volcanics

See Figure 2.2 For Cross Section A–A'.

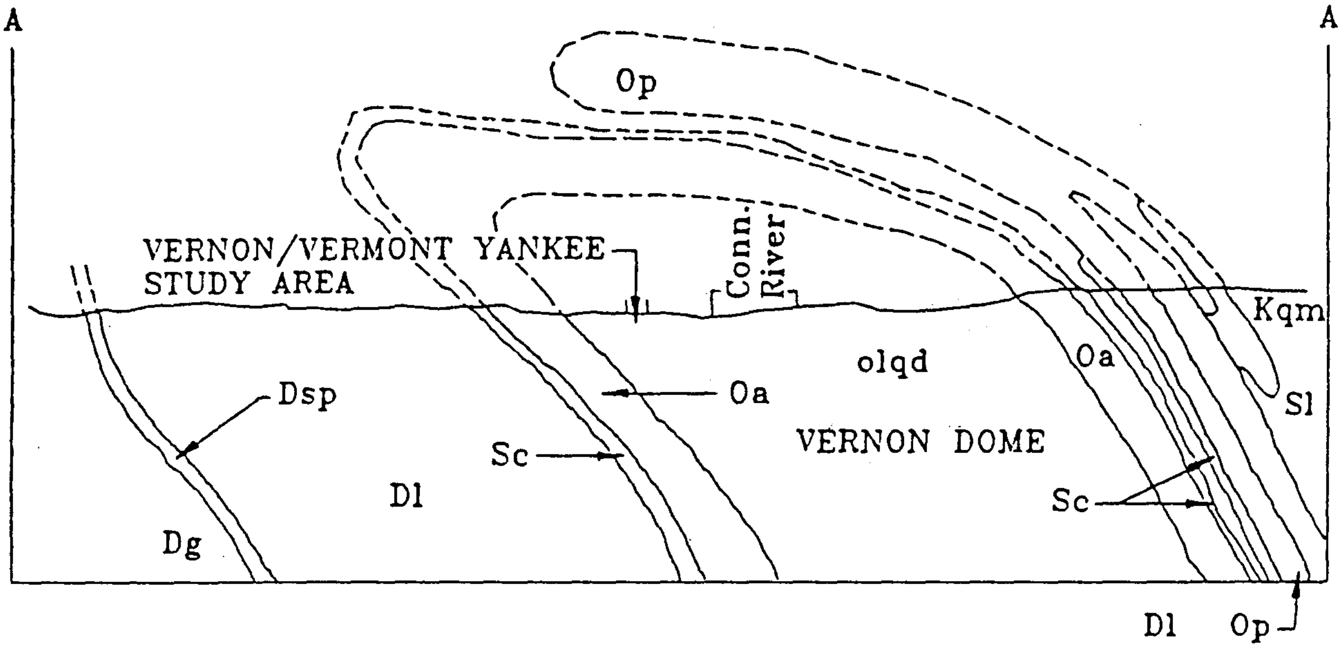


Adapted From VYNPC (1982).

MAP OF BEDROCK TYPES SURROUNDING THE STUDY AREA

Figure 2.1

figure 11A



See Figure 2.1 for explanation & location of cross section.

Vertical Scale In Feet

0 5000 10000

Horizontal Scale In Miles

0 1 2

Adapted from VYNPC (1982).

CROSS SECTION OF BEDROCK TYPES

Figure 2.2

figure 11B

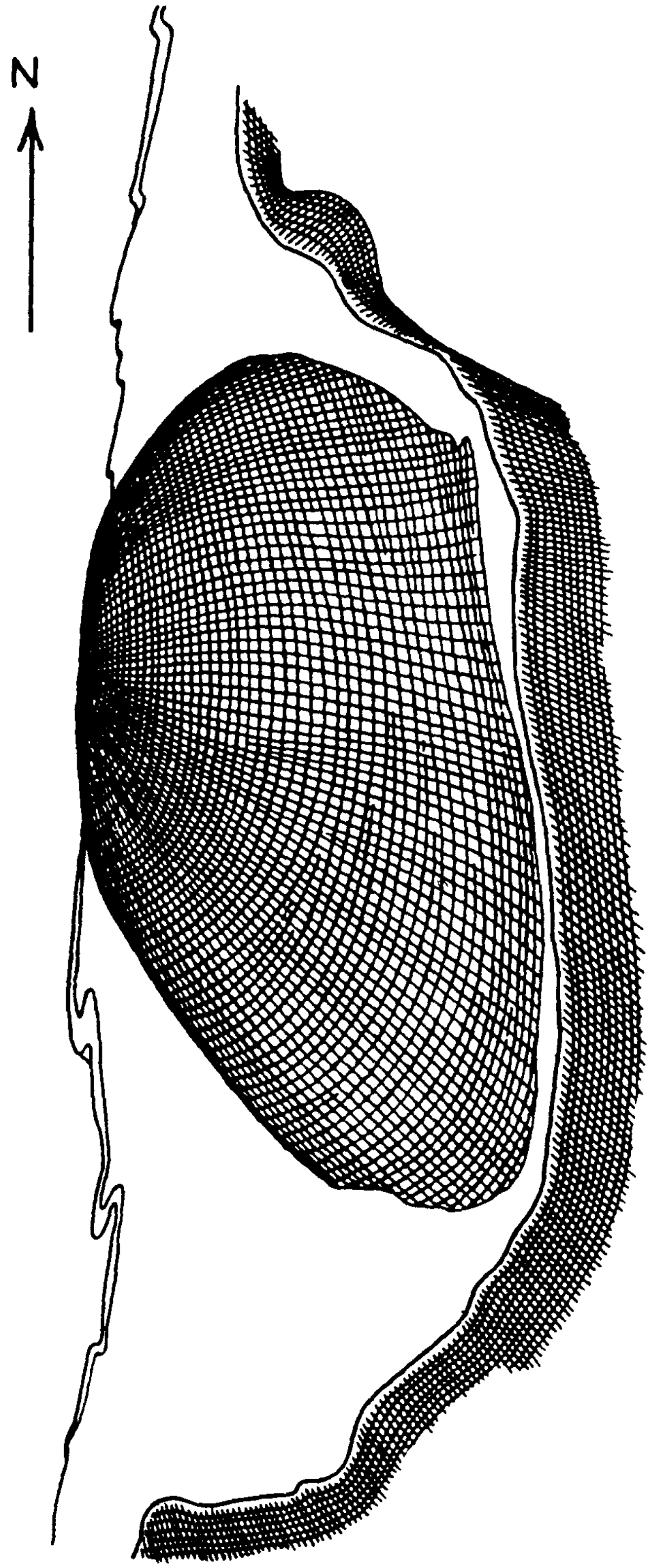


Figure 6-2. Schematic block diagram showing form of the Vernon dome. Horizon shown is the base of the Littleton Formation. View looking down and to the north.

(see figure 12). It separates the conglomerate and slate of the Littleton Formation to the east from the phyllite and thinly interbedded slates and sandstone of the Putney Formation to the west.

Post-metamorphic Faulting

The last tectonic event to have affected the rocks of the Brattleboro area is high angle, post-metamorphic faulting, presumably related to the Mesozoic rift system of the Connecticut Valley. There are two key areas where faulting is evident. Just west of the Connecticut River in Drummerston and part of Brattleboro and Putney, is an offset of the Chicken Yard line. The main movement was down on the east side, but near horizontal slickenlines at one locality indicate a late stage strike slip component. There is also a small fault in a gully on the southwest side of Daniels Mountain in Hinsdale. The Ammonoosuc, Clough and Littleton Formations offset across the gully has relative movement down on the east. The fault strikes N20^{o}E and has a stratigraphic throw of 600 feet.

The Metamorphism of the Eastern Sequence

The grade of metamorphism in the eastern Brattleboro ranges from low in the west to high in the east. The low metamorphic grade corresponds to the core of the Brattleboro syncline and extends northward along the Connecticut River-Gaspe synclinorium into Canada. Eastward, the metamorphic grade increases to the sillimanite zone over the Bronson Hill anticlinorium. Isograds generally parallel the regional north-south strike of the major features.

Bedrock History (see figures 13A,B)

IV. Glacial and Pleistocene Geology/Surficial Geology

The most recent geologic epoch, the Pleistocene, is known as the "Ice Age." During this period of about one million years, all of New England was subject to repeated episodes of continental

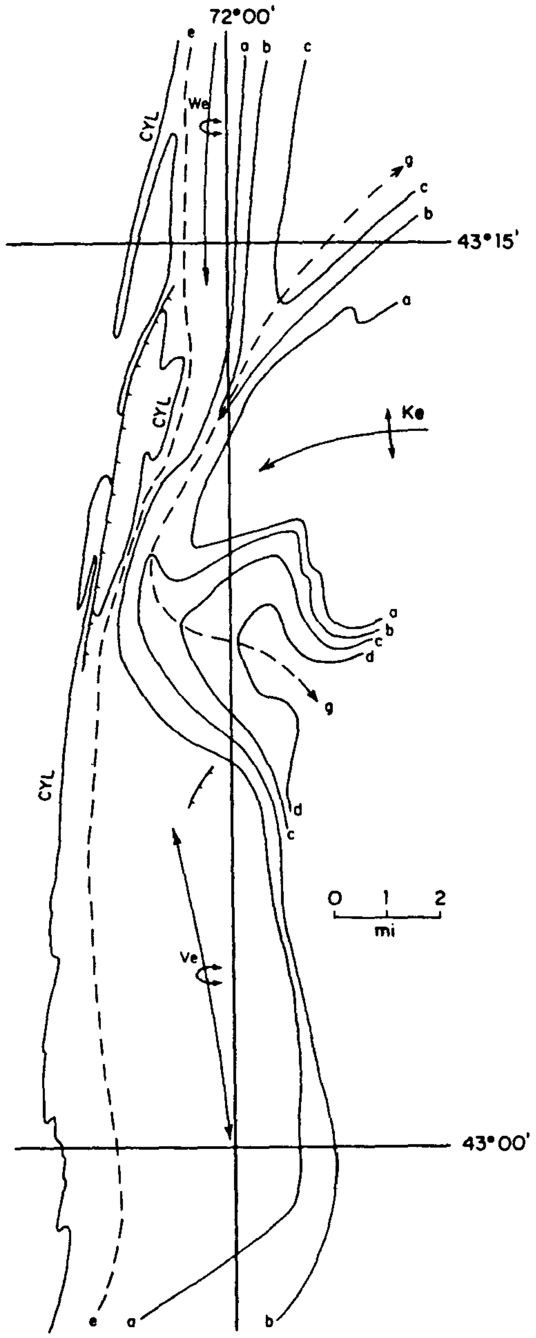


Figure 6-1. Axial elements east of the Chicken Yard line (CYL). Traces of axial surfaces of the nappe-complex are shown by solid lines. a-a is synclinal surface beneath the Bernardston nappe; b-b is the axial surface of the Bernardston nappe; c-c is the synclinal surface between the Bernardston and Skitchewaug nappes; and d-d is the axial surface of the Skitchewaug nappe. Post-nappe axial elements include: e-e, axial surface of the Brattleboro syncline; Ve, Ke, and We, the axes of the Vernon and Keene (Westmoreland lobe) domes, and of the Wellington Hill anticline, respectively; and g-g the axial trace of a major synformal fold that deforms the older axial surfaces. Arrows on g-g show plunges away from an axial culmination west of the Keene dome.

GEOLOGIC HISTORY

Connecticut River-Gaspé Synclinorium
East Flank of Green Mountain Anticlinorium

The inferred generalized geologic history of the western Brattleboro area is summarized as follows:

1. Precambrian: Development of a metamorphic complex exposed in the core of the Athens dome, approximately 1,000 m.y. ago.
2. Cambrian-Middle Ordovician: Deposition of marine sediments and bimodal volcanics (Hoosac through Missisquoi Formations) on the eroded Precambrian basement.
3. Late Ordovician-Early Silurian (Taconic orogeny): Non-deposition, probable thrusting, tectonic emplacement of small ultramafic bodies, metamorphism, uplift and consolidation, followed by erosion and development of two regional unconformities, one above and one below the unnamed schist-amphibolite unit.
4. Silurian: (A) Deposition of the sands and conglomerates of the Russell Mountain Formation over the Late Ordovician unconformity surface, followed by volcanism; (B) Development of a structural basin as a result of the Taconic events, with deposition into it of a thick sequence of mudstones (Northfield Formation), interbedded muds and calcareous sands (Waits River Formation), and interbedded sands and muds (Gile Mountain Formation), mostly under deep water conditions. Volcanic activity, largely mafic, during this time produced the Standing Pond and Putney Volcanics.
5. Lower Devonian: Deposition of marine deepwater shale (Littleton Formation).
6. Middle Devonian (Acadian orogeny): (A) Rapid burial by sediment and tectonic overburden with the development of schistosity, isoclinal folding and the onset of metamorphism. The Prospect Hill recumbent fold formed at this time; (B) A second pulse of deformation closely following the first, characterized mainly by the rise of the Guilford and Athens domes. The peak of metamorphism was reached shortly after emplacement of the domes. Intrusion of the Black Mountain granite occured late in this phase. Burial during the peak of metamorphism was on the order of 20 km; (C) Minor late folding and faulting.
7. Late Devonian through end of Paleozoic: Prolonged erosion.
8. Triassic: Faulting and dike emplacement.
9. Late Mesozoic: Continued erosion.
10. Tertiary: Epeirogenic uplift; renewed erosion.
11. Pleistocene: Glaciation; erosion followed by deposition in valleys during glacial retreat.
12. Post-Pleistocene to present: Continued erosion.

figure 13A

Bronson Hill Anticlinorium

The inferred history of the eastern portion of the Brattleboro area is as follows:

1. Ordovician: Deposition of a thick sequence of bimodal volcanics, possibly in an island arc or continental margin setting (Ammonoosuc Volcanics). Deposition of black sulfidic muds in adjacent restricted seas, following the volcanic activity (Partridge Formation). Intrusion of the Oliverian Plutonic Series.
2. Late Ordovician (Taconic orogeny): Unknown amount of crustal shortening and deformation; uplift, erosion, and development of a regional unconformity.
3. Silurian: Deposition of thin conglomerates and sandstones (Clough Formation) and calcareous rocks (Fitch Formation) by transgressing seas on the eroded highs of the Bronson Hill anticlinorium.
4. Lower Devonian: Increased rate of subsidence in the area, and deposition of a thick sequence of marine shales (Littleton Formation).

5. Middle Devonian (Acadian orogeny): (A) Rapid burial by tectonic overburden; development of schistosity, isoclinal folding and metamorphism. Large recumbent folds with "hot" rocks (i.e., high grade metamorphics) in their cores (See discussion in Thompson et al., 1968) moved westward into the area from a source further to the east; (B) Rise of domes followed closely after the emplacement of the nappes. The metamorphism, already of high grade, remained so during this second phase; (C) Intrusion of small granite bodies of the New Hampshire Plutonic Series; minor folding.
6. Late Paleozoic to present: History is similar to that of the western part of the area.

figure 13B

glaciation (see figure 14). Glaciers formed to the north and advanced southward, removing the rock mantle from the bedrock, and eroding the bedrock. As the glaciers retreated, new sediment was deposited. Thus, the surficial material of Vermont was all deposited by glaciation, except for recent stream alluvium. The major surficial deposits are till, glacio-fluvial deposits, glacio-lacustrine deposits, and postglacial fluvial deposits (see figure 15).

Till

Till is a pebbly, sandy, clayey deposit of unsorted debris left by a glacier. The composition and texture of till varies from clay to sand. Till is the most widespread surficial material in Vermont as it covers most of the uplands. Most commonly deposits are less than 25 feet thick, but deposits can vary from a thin discontinuous layer on the uplands to a thickness of 100 feet in some valleys. Most of the till in Vermont has a high sand content and a low clay content. This allows a high permeability for the till despite the characteristic poor sorting of till. Since few frontal, terminal or recessional moraines are found in Vermont, most till has been mapped as ground moraine by default. There are two types of till: basal till and ablation till (see figure 16). Basal till is a compact till containing more rounded, striated boulders with a high content of erratics. Ablation till is a loosely packed, very sandy till containing angular boulders of local bedrock.

The basal till of Vermont is a dense, compact till that varies in color and texture with the incorporation of local bedrock. The clay content of this till is < 30% and in most samples is < 10%. The silt content is usually higher than the clay content. The basal till contains more erratic fragmental material than ablation till and these fragments are more rounded and faceting is more pronounced. Due to the high sand content, water penetrates basal tills to considerable depths.

Ablation till in Vermont has a high sand content, little or no clay, angular boulders and cobbles, and a high percentage of fragments composed of local bedrock. The till is composed of < 15% clay,

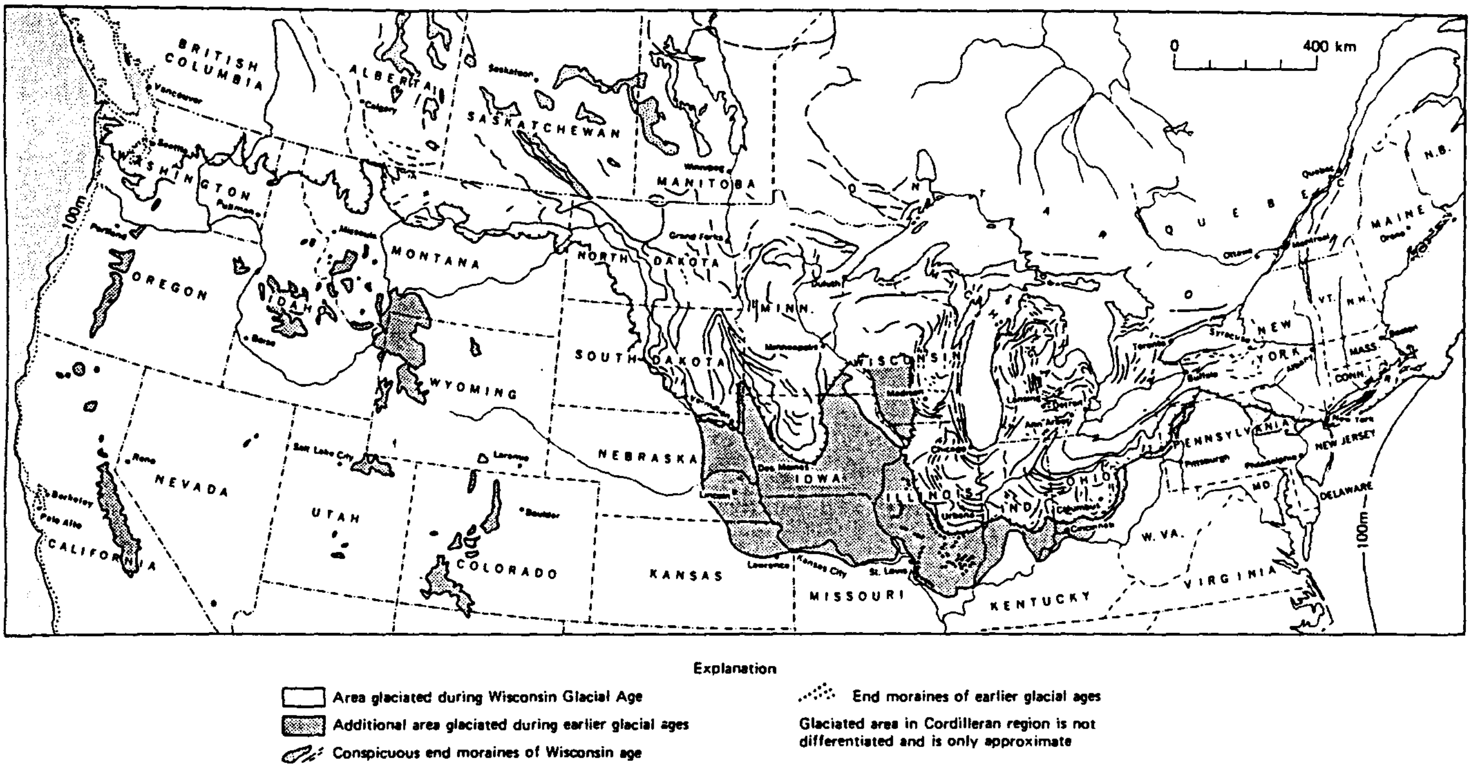


Figure 18-11 Extent of glaciation in northern United States and southern Canada, showing lobation induced by configuration of the terrain beneath the ice. At maximum extent of glaciers, shoreline may have stood near -100m isobath.

figure 14

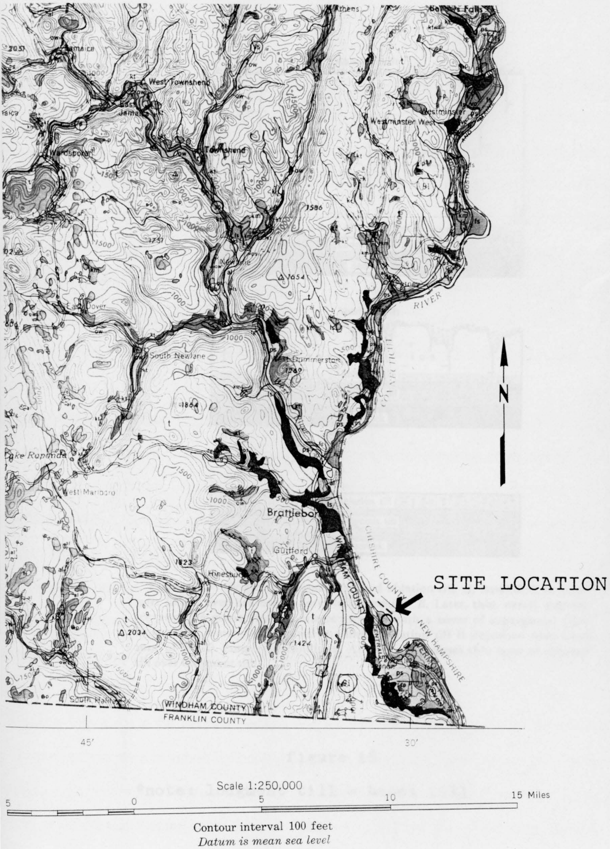


figure 15

GLACIOLACUSTRINE

lg	bg	dg	d

LITTORAL SEDIMENT
PREDOMINANTLY GRAVEL

lg—horizontally bedded gravel deposited in a shoaling lake or topset beds of deltaic gravel where no foreset bedding is exposed.
bg—beach gravel.
dg—delta gravel showing foreset bedding.
d—small deltas composed of sand and gravel.

ls	ps	bs	ds

LITTORAL SEDIMENT PREDOMINANTLY SAND

ls—well sorted sand, no pebbles or boulders.
ps—pebbly sand.
bs—sand containing ice rafted boulders.
ds—delta sand.

POSTGLACIAL FLUVIAL

fg

FLUVIAL GRAVEL

fs

FLUVIAL SAND

al

RECENT ALLUVIUM

Fluvial sands and gravels were differentiated in areas where the deposits might have economic significance.

PLUVIAL

p

SWAMP, PEAT and/or MUCK

BEDROCK

BEDROCK EXPOSURES

Significant exposures of bedrock with little or no cover that show the thinness of the drift, or where the drift has been removed by erosion. No effort was made to differentiate all outcrops in till areas of the uplands.

FROM
SURFICIAL GEOLOGIC MAP OF VERMONT

Compiled and Edited under the Direction of
Charles G. Doll, State Geologist

Geology by
David P. Stewart, Miami University and Paul MacClintock, Princeton University

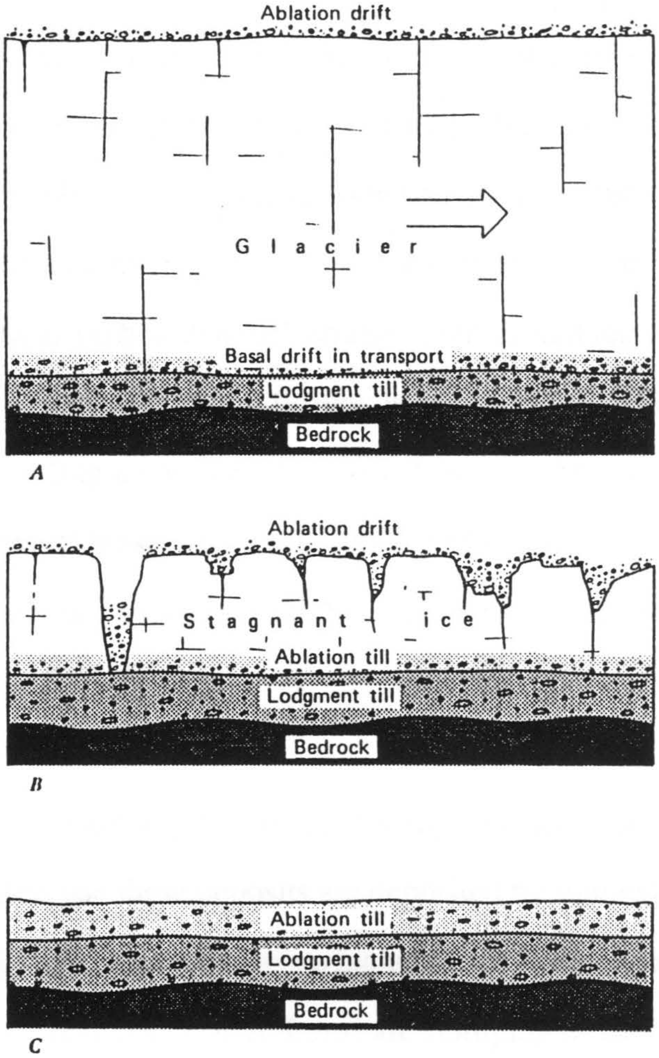


Figure 7-16 Origin of lodgment till and ablation till. *A*. Basal drift in transport lodges over bedrock to form lodgment till. *B*. Later, thin, nearly stagnant ice near the glacier margin wastes away beneath a cover of superglacial drift, from which water has removed the fines. Ablation till is deposited from basal zone of ice. *C*. Postglacial condition. Ablation drift forms thin layer of ablation till over lodgment till.

figure 16

*note: lodgment till = basal till

65-88% sand and 10-35% silt. In Vermont, ablation till may or may not overlie another more compacted till. In many areas ablation till lies directly over bedrock, but in others it covers a basal till. Much of the fragmental material in ablation till was transported only a short distance as is evidenced by the angularity of these fragments and the large amount of local bedrock. The till resembles a residual bedrock mantle, but striations on boulders and erratics from distant regions identifies this material as till. A certain amount of sorting and stratification is common in ablation till. The till may be crudely bedded and separation of fragments according to size is sometimes apparent. Sand lenses and stringers and to some extent gravel lenses are not unusual. The degree of sorting and the amount of sorted material varies greatly from one locality to another, but there is a rather constant sorting factor locally.

Glacio-fluvial Deposits

Glacio-fluvial deposits include all ice-marginal and proglacial materials deposited by meltwaters from glacial ice (see figure 17). Because these deposits are deposited by running water, they are sorted and stratified. Ice marginal or ice contact deposits include kames, kame terraces, kame moraines and eskers. Characteristic features of these forms are slumping or ice contact structures, which formed when the ice against which they were deposited melted away. Proglacial deposits consist chiefly of outwash plains or outwash aprons and valley train or spillway deposits. No outwash plains or aprons beyond the terminus of former glacial borders has been identified in Vermont.

Possibly important to the Vermont Yankee area are kame terraces and spillway gravels (see figure 15). Kame terraces are a common ice contact deposit in Vermont. In some areas kame terrace gravel contains a high percentage of fine sand and or silt. The sand/silt content is especially high in kame deposits in valleys that formerly contained ice dammed lakes, since gravel was deposited into the

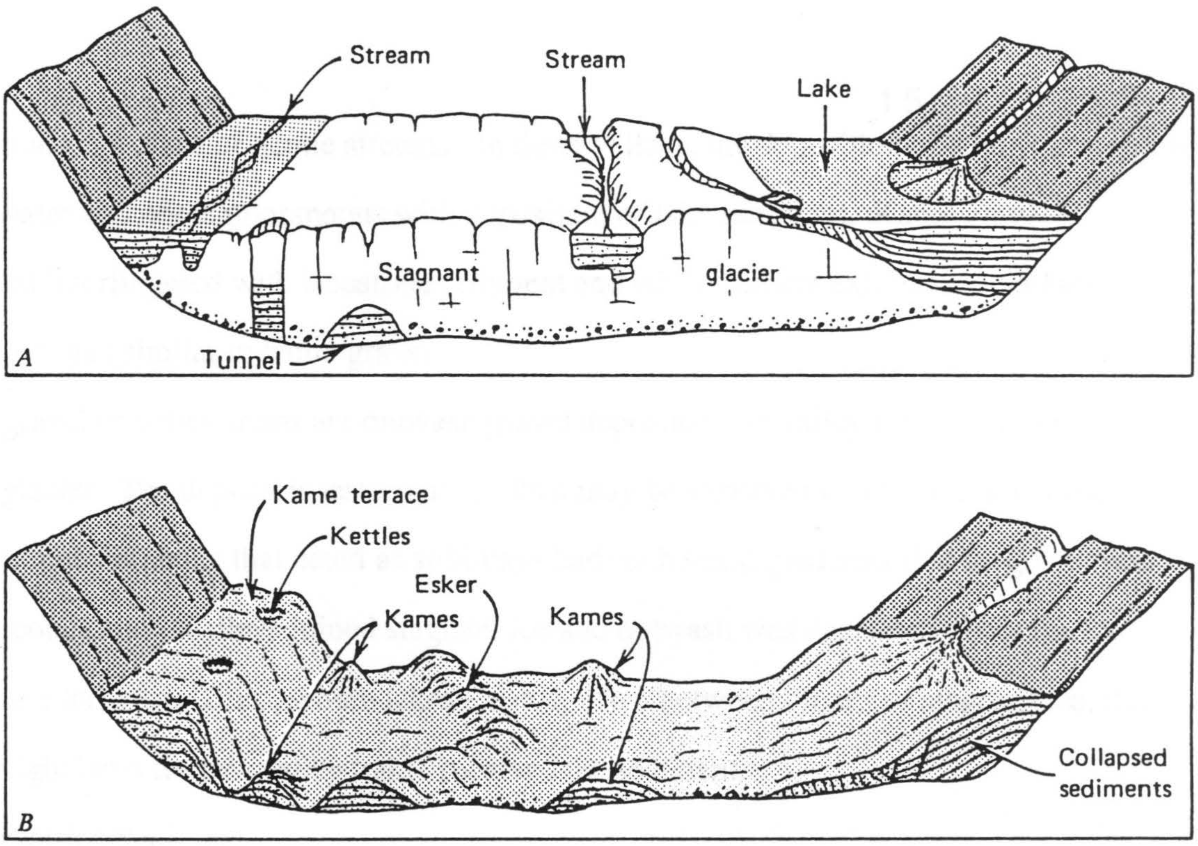


Figure 8-4 Origin of bodies of ice-contact stratified drift. *A*. Stagnant glacier ice affords temporary retaining walls for bodies of sediment built by streams and in lakes. *B*. As ice melts, bodies of sediment are let down and in the process are deformed.

figure 17

waters of ice marginal lakes or gentle streams. In these valleys, the deposition of kame terrace gravel was in slack water and contemporaneous with deposition of lake sediment. Kame gravel is interbedded and interfingered with lacustrine sediment and lake sediment exhibits ice-contact (slumping) structures similar to kame gravel.

Spillway gravel or valley trains are outwash gravel deposited in a valley that acted as a spillway for a melting glacier. The deposit is less common than may be expected in Vermont for several reasons. First, many streams that acted as spillways had such steep gradients that no gravel was deposited. Second, many valleys joined stagnant ice and outwash was deposited along the ice margins as kame terraces. Third, where lakes existed, often between blocks of stagnant ice, the detritus that might have formed valley trains became lake sediment.

Glacio-lacustrine Sediment

Lacustrine sediment is most common in stream valleys and lowlands of Vermont. This is because drainage in these areas was restricted, and as stagnant ice melted, small lakes formed. Larger lakes were dammed by advancing and retreating glaciers, and some were dammed by glacial deposits. Lakes also formed along ice margins as it melted and thus lake sediment is often found in isolated patches at high altitudes (see figure 17). Such lakes covered vast areas of Vermont (see figure 18) and left vast amounts of lake sediment.

Lake sediment can be grouped into three categories. Silts and clays were deposited in the deeper parts of the lake (bottom sediment), sands in the shallow water (littoral sediment), gravels on beaches. Deltas also formed at the lake margins, where tributaries entered the lake.

Valley lakes were not universally slack water bodies, as down-valley currents were often present. In most cases, earlier lakes were the highest, with lake level subsequently lowered. A great amount of water and sediment was carried into the lake by tributary streams. Melting ice, especially in the

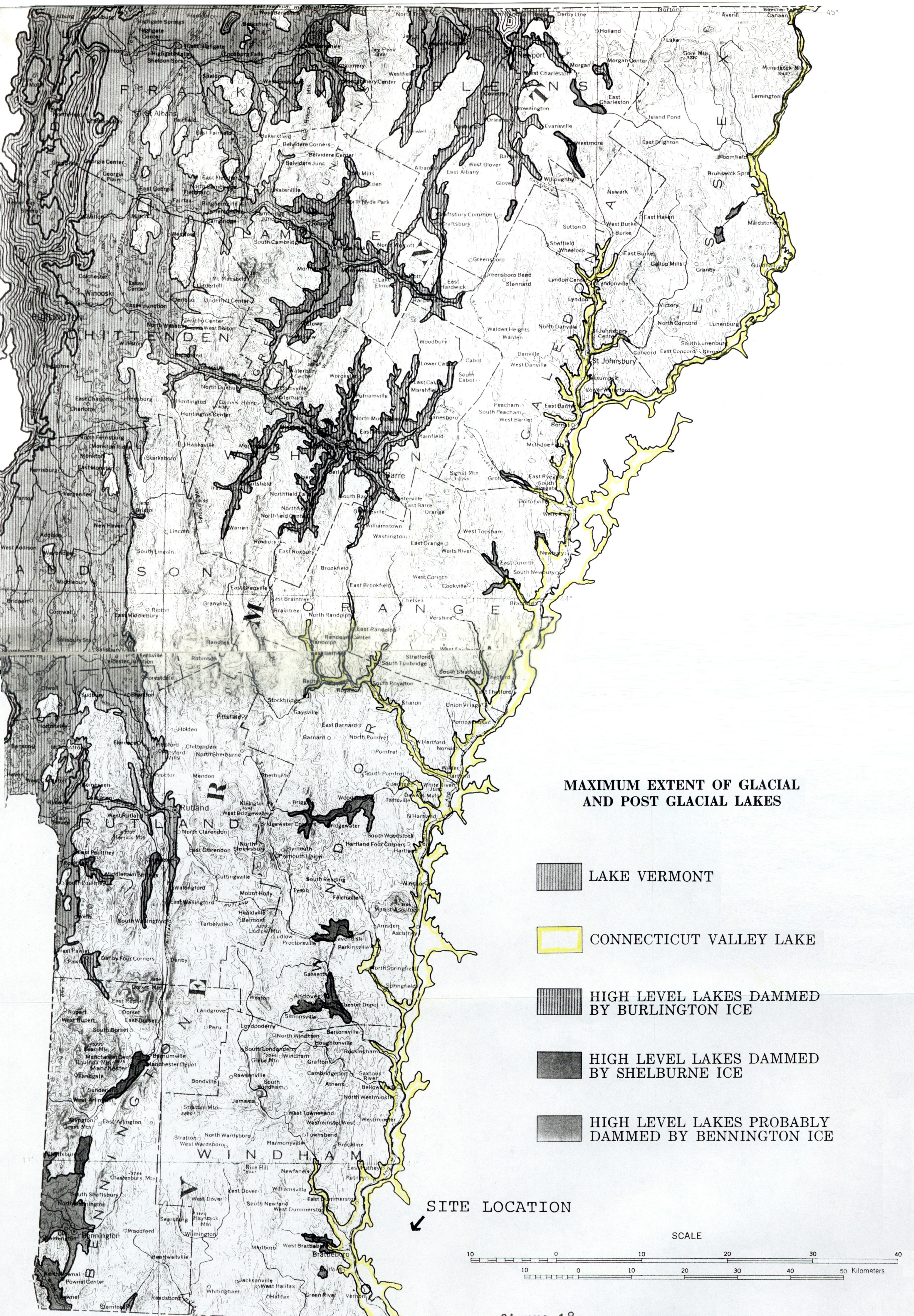

MAXIMUM EXTENT OF GLACIAL AND POST GLACIAL LAKES
LAKE VERMONT
CONNECTICUT VALLEY LAKE
HIGH LEVEL LAKES DAMMED BY BURLINGTON ICE
HIGH LEVEL LAKES DAMMED BY SHELBURNE ICE
HIGH LEVEL LAKES PROBABLY DAMMED BY BENNINGTON ICE
SITE LOCATION
SCALE
10 0 10 20 30 40
10 0 10 20 30 40 50 Kilometers

figure 18

case of marginal lakes also supplied a great amount of sediment. The large amount of sediment often so completely filled the valley that shoaling occurred. A block of stagnant ice often partially filled the valley particularly in the early stages of the lake. Because of this, deposits made in glacial lakes are often significantly modified. Down-valley currents formed cut and fill structures and undercut deposits causing slumping. Cross-bedding is also common. When melting occurred, ice-contact structures were formed by slumping of the lacustrine sediment.

As shoaling took place, sediment began to completely fill the valley and as the level of sediment approached the level of the water, the type of sediment changed from silt and clay to sand, pebbly sand and finally to gravel. In this manner, valleys completely filled in a relatively short time. In valleys such as the Connecticut River Valley, this is also the reason why glacio-lacustrine deposits progress from fine to coarser grain size with increasing elevation (see figure 15). In some valleys, the top layer of gravel is quite thick and in others the sand contains a high percentage of pebbles. Shoaling gravel in some cases may be the topset beds of a deltaic deposit rather than lacustrine gravel.

The high velocity of streams that flowed from the mountains and the volume and types of sediment they carried into the lakes formed deltaic deposits. Because of the large amount of sediment, deltas could be built in a relatively short time. Because of the steep gradient, a wide range of different sized sediment including large boulders was deposited. Larger fragments are not conspicuous in the foreset beds since they drop out before the delta is reached or role to the bottom of the foreset slope. As deltas build up to near lake level, however, topset beds begin to develop on the delta and at this stage, large boulders are deposited in the topset beds. Because of this, topset beds are difficult to distinguish, since they resemble recent stream deposits or kame terrace gravel. Deltas can be distinguished however, by their foreset beds. For this reason, the term "lake gravel" was used on the state map to designate the shoaling gravel and topset beds of deltas that do not exhibit underlying forset beds.

In Vermont, lake sediments are commonly found in valleys above kame terrace gravel that was deposited along the margins of stagnant ice-masses in the valley bottoms. This relationship shows that the stagnant ice against which the kame gravel was deposited had mostly melted away allowing lakes to occupy the valley prior to deposition of fine lake sediment.

Glacial Erosion

In Vermont, the most important factors affecting glacial erosion, were topography, and structure, fabric and hardness of the bedrock. The topography had two key impacts. First, topography alters or inhibits the movement of glaciers. Most of the topography in Vermont, most importantly the Green Mountains, are oriented north-south. As ice piled up to cross the mountains, it moved parallel to the mountains through stream valleys, cols, and gaps in mountain crests, concentrating erosion in these places. Second, erosion is concentrated in pre-glacial stream valleys. Where streams are perpendicular to glacial advance, they in general fill with sediment. Where stream valleys are parallel to glacial advance, erosion is maximized and valleys are deepened and sides steepened. The relative hardness, structure, and fabric of the bedrock generally controlled erosion in many areas. Softer rocks were eroded more heavily. Features created by the ice, parallel the fabric of the rock. Lakes occupy basins cut in softer rock while ridges and outliers are composed of harder rock.

The Connecticut River Valley is an example of glacial erosion of a valley trending more or less parallel to the glacial advance. Ice invading the valley was deflected down-valley and as a result, the valley deepened and widened, leaving steep valley walls which rise abruptly from the valley floor. The bedrock along the course of the valley had variable hardness and therefore erosion was more intense in some sections than in others. Thus, the valley is wide in some sections, and narrow in others. Also in some reaches, thick accumulations of sediment indicate deepening and in other locations outcrops of bedrock indicate less erosion

Glacio-fluvial Erosion

There are two categories of glacio-fluvial erosion. First, is erosion by streams beyond the melting ice margins that acted as spillways for the meltwater. These streams carried large amount of water and were highly erosive. Many of the major stream courses were occupied by lake waters during early stages of deglaciation. Second, are subglacial, englacial, and superglacial streams which flow under, in and on glaciers respectively. These streams are supplied by meltwater and can cause much erosion, however, only subglacial streams or streams which plunge to the bottom of a glacier erode the land surface.

Problems of Correlation of Till

Many factors in the geology of Vermont complicates the correlation of till: rugged topography, complex bedrock, multiple glaciation, absence of weathering zones between tills and an absence of datable organic remains. First, rugged topography complicates the advance and retreat of glaciers. The peripheral zone of the glacier stagnates after it thins to a level below the tops of the mountains. The confined masses of stagnant ice then thin by downwasting until they finally only occupy the stream valleys. Thus glaciers do not maintain stable margins that would form frontal moraines and outwash is carried away by streams with steep gradients and high velocities. Thus outwash aprons do not mark the marginal positions of the ice. Also, numerous ice marginal lakes form in and around the masses of stagnant ice as soon as the ice thinned and was confined between valleys. Melting was greatest at the contact point with the mountain, so lakes were common in these areas. Lakes also formed in the valleys after the ice melted to a series of disconnected blocks. The deposits formed are a mixture of glacial outwash, lacustrine sediment, and till.

Second, the bedrock of Vermont is very complex and because of this or in spite of it, the mineralogy of various rock units are not significantly different. Thus there is little difference between till sheets from different parent rocks. Also, because of the climate, chemical decomposition is more prevalent than physical break down. The break down of mafic minerals is most rapid and produce suites of secondary minerals that are essentially the same for all rocks containing these minerals.

Third, in regions where there is multiple glaciation, tills become more similar with each succeeding glacial invasion. Each advance removes drift of former glaciations and mixes the debris of former deposits with the bedrock load it has acquired. Also, till sheets in Vermont are very sandy and contain little clay or organic matter to bind the till. The till is thus easily broken up by overriding ice and subsequent intermixing during transport.

Fourth, because of the relatively high permeability of the till , water penetrates deep into the till, increasing chemical decomposition and making weathered zones between tills. Fifth, a lack of organic remains does not permit the use of carbon 14 dating.

The Pleistocene

The Pleistocene is divided into four intervals corresponding to four episodes of glaciation. From oldest to youngest these are the Nebraskan, the Kansan, the Illinoian and the Wisconsin. An interval of deglaciation, in which temperatures rose followed each period of glaciation. From oldest to youngest these are the Aftonian, the Yarmouth, the Sangamon, and the Post-Cochrane (interval since retreat of last glaciers).

The glacial deposits of Vermont are believed to be Wisconsin in age, so it is this subdivision which will be studied here. Like the Pleistocene, the Wisconsin is subdivided into periods of glaciation and deglaciation. From oldest to youngest, these are the Farmdale substage, the Farmdale-Iowan interval, the Iowan substage, the Iowan-Tazewell interval, the Tazewell substage, the Tazewell-Cary interval, the Cary substage, the Cary-Mankato interval, the Mankato substage, the Two Creeks interval, the Valders substage, the Valders-Cochrane interval, the Cochrane substage, and the Post-Cochrane interval.

Glaciation

Glaciation is the covering of any part of the Earth's solid surface with glacier ice, or its water surface with floating glacier ice or shelf ice. Deglaciation is the process of uncovering any area by the waning of glacier ice or shelf ice. Flint (1971) identified several types of glaciers. Cirque glaciers form on the sides of mountains and flow down slope to a valley where they may merge with other glaciers. A valley glacier is a glacier that flows down a valley, bounded by exposed rock. Its width is generally small in proportion to its length. An ice sheet is an enormous mass that buries all but the very highest points of the underlying ground. It flows outward from one or more central areas. There are two intermediate types of glaciers. A piedmont glacier is an intermediate between valley glaciers and ice sheets, which occupy broad lowlands at the base of steep mountain slopes. Each is the spreadout, expanded, terminal part of a valley glacier descending the highland or the coalescence of several valley glaciers. A mountain ice sheet is a glacier that overlies or originates in two or more mountain masses, burying all but the highest peaks. All these types of glaciers constitute a gradational sequence. Ice sheets form from the coalescence of valley glaciers which formed from cirque glaciers. Valley glaciers spread out on lowlands as piedmont glaciers and gradually thickened until almost all mountain summits were submerged.

Figure 19 shows this sequence as it relates to "alpine glaciation." Figure 19A shows a mountainous highland before glaciation. Figure 19B shows some firn (recrystallized snow) banks enlarged to form cirque glaciers and short valley glaciers. Firn and ice are more abundant on slopes facing the right where the incidence of solar heat is least. Meltwater from ice and firn carry rock down steep valleys and deposits sediment in the less steeply sloping main valley. In figure 19C,

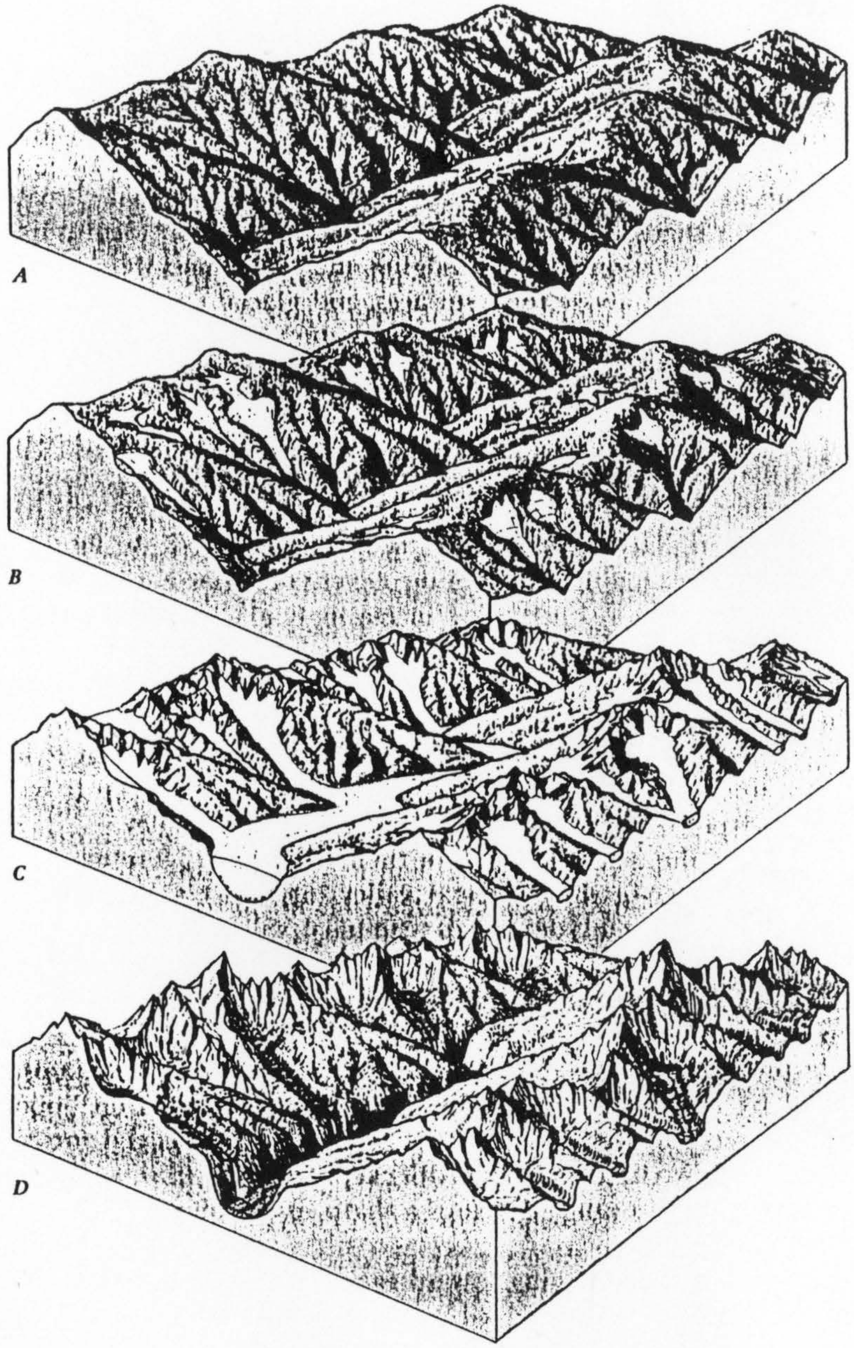


Figure 6-3 Alpine sculpture. *A*. A mountain highland before glaciation. *B*. Growth of firn banks and small glaciers. *C*. Development of a network of valley glaciers. *D*. The same area after deglaciation, showing glaciated troughs, rock basins, faceted spurs, hanging tributary valleys, cirques, arêtes, cols, and horns.

figure 19

expanding glaciers coalesce to a valley glacier in the main valley. Glacier occupied valleys are widened and deepened, with tributary valleys left hanging above them. Spurs between tributaries are blunted and beveled as larger glaciers move past. As the main valley is enlarged, it becomes straighter. The crests of the mountains are sharpened by frost wedging. Cirques on opposite sides of the crests reduce the crest to an arete, or sharp ridge. Where two cirques enlarging towards each other cut through the ridge that separates them, a sharp edged gap or col, with a smoothly curved profile results. A horn forms where three or more cirques erode a single high part of the mountain crest. Figure 19D, shows the post-glacial terrain.

This was not quite the type of glaciation which occurred in Vermont. Rather than "alpine glaciation," Vermont experienced glaciation by ice sheets, which advanced, generally from the north (see figure 20). The ice sheets would have thickened to the north so that the thinner leading edge of the ice sheet was probably diverted down existing drainage patterns. These initial lobes of ice would be valley glaciers. At this point, alpine glaciation may have occurred. As the advance continued, the system of valley glaciers, enlarged to the ice sheet, which buried the summits except for scattered peaks. Horns and aretes were ground down to form domelike peaks and rounded ridges and cols were smoothed, deepened and broadened.

There are three accepted glacial advances and possibly a fourth. A pre-Bennington glaciation of north-central Vermont is suggested by some studies (Stewart and MacClintock ,1969). The next glaciation was the Bennington Glacial Stade. The Bennington glacier advanced from the northwest and covered all of Vermont and probably all of New England. The absolute age can not be determined but it is assumed to be in the early Wisconsin Stage. The Bennington till is a dense basal till which has been overridden by subsequent glaciation except perhaps in southwest Vermont where it forms the surface till. The till is 40-60% sand, 25-50% silt and 5-20% clay. Local bedrock accounts

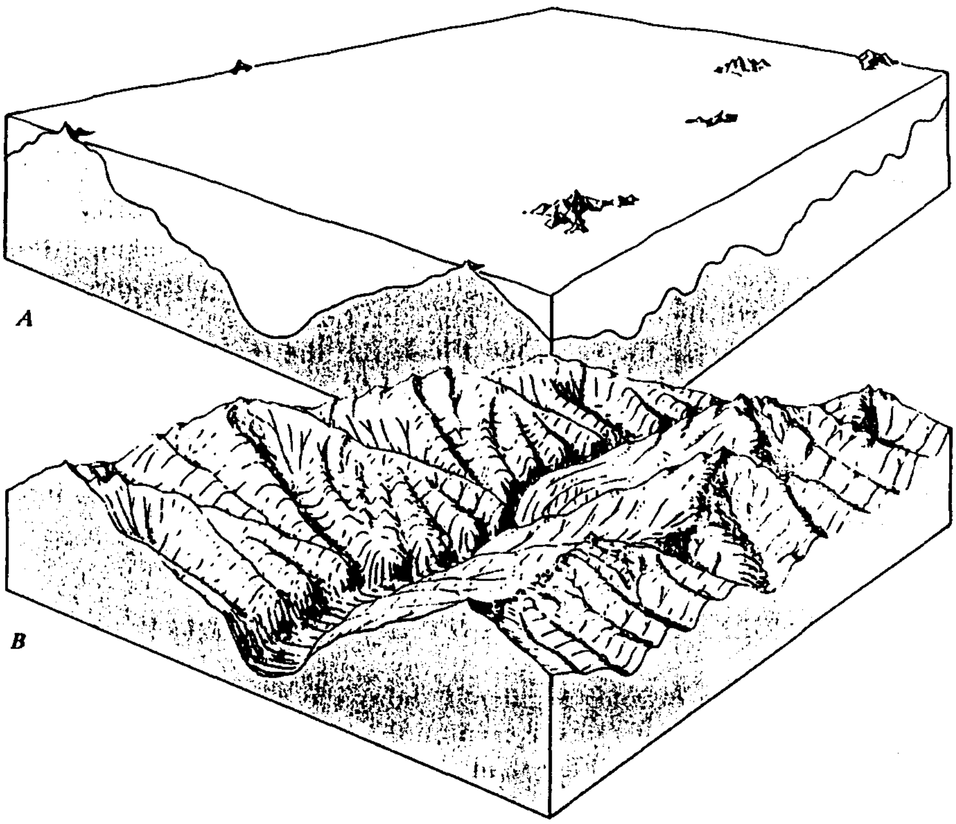


Figure 6-4 Sculpture by a mountain ice sheet. *A*. The area of fig 6-3 *D*, buried beneath a mountain ice sheet. *B*. The same area after rapid deglaciation, showing smoothing and rounding of the formerly buried surface, contrasted with the reduced but frost-sharpened former nunataks.

figure 20

for about 75% of fragmental material. Cobbles and boulders are rounded, faceted and striated.

The West Norwich Interstade is named for the section exposed in a roadcut 1.5 miles northwest of a cross roads designated West Norwich on a topographic map of Hanover Quadrangle. At this location seven feet of calcareous Shelburne till with northeast fabric overly Bennington basal till with a ten foot leached zone at the top. Fifteen feet of calcareous basal till having a northwest fabric is exposed below the leached zone. This is the only significant evidence found by 1969 of an ice-free interval of interstadial duration between Bennington and Shelburne stade in Vermont. Lacustrine sediment overlying Bennington till and below Shelburne till is found in exposures throughout the state suggesting extensive lakes during and after retreat of Bennington ice from the region.

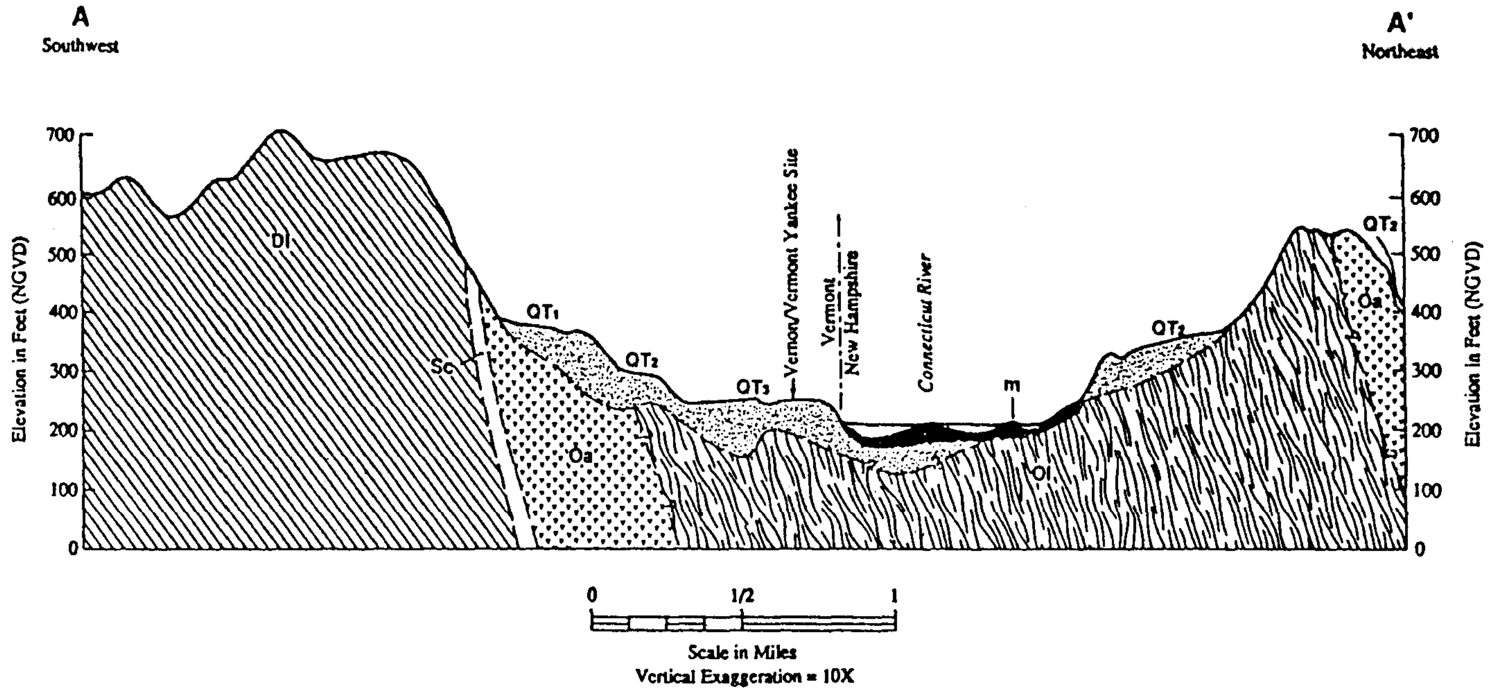
The next glaciation was the Shelburne glacial stade. The Shelburne glacier advanced from the northeast and covered all of Vermont with the possible exception of the area between Bennington and Brattleboro in southwest Vermont. The ice moved down the Connecticut River Valley into Massachusetts and probably as far south as southern Connecticut and at least western New Hampshire. In Vermont, the Shelburne drift is predominately an ablation till, although a basal till is found in all parts of the state. The Shelburne till is thin and may be only a thin veneer on the surface. Shelburne till may cover older till or lie directly on the bedrock. The Shelburne ablation till has a sandy, loose texture, a high percentage of angular cobbles and boulders composed of local bedrock.

Stewart and MacClintock (1969) postulated that there may have been two northeast till sheets. First, is the till which forms the surface east and south of the Burlington till and north of the southern margin of the drift sheet lying between Bennington and Brattleboro. This till is a loose, sandy ablation till. Second, northeast till also occurs under Burlington till in Northwest Vermont. This till is a compact basal till with a higher percentage of silt and clay than ablation till. It is assumed however that both these tills were deposited by the same glacial invasion.

Outwash sediments deposited during the Shelburne Stade are scattered over the region covered by the Shelburne ice. The outwash is in the form of kame gravel in terraces, moraines and eskers. The kame deposits of Shelburne Stade are not as well developed or as massive as those of Burlington age, and most of these deposits are small and isolated. The Shelburne kame deposits located in valleys formerly occupied by ice-marginal and post-glacial lakes are more sandy and silty than those located in other areas. Kame gravel deposits are scattered through the Connecticut River Valley and its tributaries. Much of the gravel formerly thought to be kame terrace has been reclassified as lacustrine gravel and pebbly sand deposited during shoaling of the Connecticut Valley lakes (lake Hitchcock). Most kame gravel is found along tributary streams.

The Lake Hitchcock Interstade is the ice free interval during which Lake Hitchcock occupied the Connecticut River Valley and much of its tributaries (see figure 18). It is assumed that this lake (or perhaps lakes) formed during the final melting stages of the Shelburne Ice. Lakes higher than the stable Lake Hitchcock were common along the sides and between blocks of stagnant ice, as well as upstream from ice-dams in the tributary valleys. Lake Hitchcock remained in the valley long after the glaciers had melted, being in existence for at least 2,300 years. Lake Hitchcock extended from Middleton Connecticut where the valley was dammed by glacial moraine deposited by Shelburne ice, to the Canadian border. Lake sediments thus form most of the unconsolidated deposits in the Connecticut River Valley and its tributaries from the Massachusetts border to the Canadian border. Deltas built into the lake at the mouths of tributaries are also common deposits. Most of the deltas were removed by subsequent stream erosion or covered by lacustrine gravel during shoaling.

Since the interstadial, erosion has lowered, dissected and modified these deposits. After the dam that formed Lake Hitchcock was breached, the Connecticut River was re-established. As the river incised a new channel in the glacial valley fill, it left step-like erosional terraces (see figure 21).



NOTES

1. See Figure 2.3-2 for explanation of geologic symbols and profile location.
2. Geologic contacts are interpreted from geologic mapping and site characterization borings.

SITE AREA
GEOLOGIC PROFILE A-A'

Figure 2.3-3

Along with this downcutting, the river deposited a veneer of fluvial sediments on these terraces. The cumulative downcutting of the river over the past 11,000 to 14,000 years has been about 250 feet, based on the maximum height of terrace deposits in the vicinity. The rate of erosion was probably greatest shortly after the drainage of Lake Hitchcock because isostatic uplift that followed the retreat of the glaciers tilted the region southeastward at a rate of rise of over four feet per mile throughout the region (Hanson, 1991).

The Burlington Stade was the third and final glaciation. Glaciers invaded from the north-northwest, and covered the northwestern and north-central regions of Vermont. The Burlington ice first invaded the Champlain Lowland and piled up along the western slopes of the Green Mountains as far south as Rutland and the western foothills of the Taconic Mountains between the Castleton River and the Batten Kill. Ice thickened in the lowland until the ice was high enough to move over the Green Mountains north of Brandon. Ice moved down the eastern slopes of the mountains and terminated in the valley of the Third Branch of the White River between Bethel and Roxbury, the Dog River Valley between Roxbury and Montpelier and the Stowe Valley between the Winooski and Lamoille Rivers.

Correlation of Vermont Pleistocene

The correlation of the Pleistocene in Vermont with the stratigraphic sequence of North America is uncertain, because of a lack of datable organic remains. However, Stewart and MacClintock (1969) feel relationships of the substages of the Wisconsin can be inferred by comparison with the Pleistocene stratigraphy of New York, Quebec and New England. It is assumed that the till of Vermont is Wisconsin in age. This is because the leaching and decomposition of the oldest till (Bennington) is not sufficient to suggest an older age, and because radio carbon dates in New England and Quebec are all less than 60,000 years B.P.

Correlation with the St. Lawrence Lowland of New York and southeastern Quebec suggest the following. The Burlington till corresponds to the same glacial stade as the Fort Covington of New York, or the Lenoxville of southeastern Quebec. The Fort Covington is believed to correlate to the pre-Two Creeks, probably the Port Huron (Mankato) Substage of the Wisconsin Stage. From carbon dates of New York and Quebec, the Burlington ice probably melted from Vermont prior to 12,500 years ago. The Shelburne till is believed to correspond to the Malone till of the St. Lawrence Lowland. The Malone till is believed to be of Cary age. The Bennington till possibly correlates with a till older than 41,500-54,000 years B.P. in southeastern Quebec, and no correlation of the Bennington has been found in the St. Lawrence Lowland.

Correlation with other areas of New England

Radio-carbon dates of organic remains in a sediment separating an older till from a younger till give ages of 38,000 B.P. in Maine, 40,000 B.P. in Connecticut, and 38,000 B.P. in Massachusetts. The Bennington till corresponds to deposits dated at about 40,000 years. According to Schafer (1967), the last glaciation reached its maximum extent 19,000-20,000 years ago. The Shelburne till possibly correlates to deposits made by the last glacial interval. However, there may have been a glacial readvance 13,000-14,000 years B.P. Stewart and MacClintock (1969) postulate this readvance may have extended the length of the Connecticut River Valley to Middleton Connecticut, while the Burlington glacier covered northeastern Vermont. This clouds the interpretation of the surface ablation till with northeast fabric (Shelburne) in central and northeastern Vermont and the basal till with northeast fabric under the Burlington till in the northwestern part of Vermont. If the Shelburne till of eastern Vermont was deposited by the readvance that terminated in Middleton Connecticut 13,000-14,000 years ago, then it may be essentially contemporaneous with the Burlington till and older than the northeast till below the Burlington. It is also possible that the

Middleton readvance was of the Cary stade and that the Burlington was deposited later during the Port Huron (Mankato).

V. Site Characterization

Climate and Regional Physiography

In general, the climate of the site is continental. Precipitation averages 43" per year. The Vermont Yankee Site is located in the Vermont Piedmont Section of the New England Upland Section. The area lies in the Connecticut River drainage basin. The Connecticut River drains the region to the south. Major drainage patterns are of pre-glacial origin. Glacial deposition was concentrated in the valleys, with only a thin veneer of till in the uplands.

Summary of Regional Geology

The site is located in the Western New England Foldbelt Tectonic Province of the Appalachian mountains (Hanson, 1991). The site is located on the Vernon Dome on western limb of the Bronson Hill anticlinorium (see figures 6,7,11A). Although the Connecticut River Valley was well established prior to Quaternary time, present-day geomorphic features are largely the result of Quaternary processes. Multiple Pleistocene glaciations and deglaciations occurred in the region. A thin veneer of till directly overlies the bedrock of the surrounding highlands. This till relates to the Shelburne Glaciation. The lack of older glacial deposits reflects the scouring of earlier deposits by the last glaciation. An interstadial period known as the Lake Hitchcock Interstade followed the Shelburne Glaciation. The Connecticut River Valley was filled with glacio-fluvial and glacio-lacustrine deposits during the Pleistocene, most sediment being deposited in Lake Hitchcock (see figure 18). Glacio-lacustrine sediments in the area show a depositional progression from fine to coarser grain size with increasing elevation (see figure 15). This is because, the lowermost deposits in Lake Hitchcock consisted of varved clay and laminated silt, but later lacustrine deposits became increasingly coarser grained as the lake filled in and littoral deposition predominated. The valley fill floodplain was about 250 feet above the present Connecticut River and over 350 feet above the pre-existing bedrock river channel, in the site area. After the dam that formed Lake Hitchcock was breached, the Connecticut River was re-established, and as the river incised its new channel in the valley fill, it left step-like erosional terraces on the valley walls. The river also deposited a thin veneer of fluvial sediments on these terraces (see figure 21). In the Connecticut River Valley, subsequent stream erosion downcutting through glacial sediments has also produced oxbow lakes, and meander scars.

Site Geomorphology

The Vermont Yankee site is located in the Connecticut River Valley, on a meander scar, about 700 feet west of the Connecticut River. One mile downstream, the Vernon Dam, regulates the flow of water in the river (see figure 22). The site occupies the lowest of a series of stream terraces that are located on the valley walls above the floodplain (see figures 21,23,24). These terraces are underlain by glacio-lacustrine sediments, with a thin veneer of fluvial deposits on their surfaces.

The lowest terrace (see figure 24) was created in the latest stage of stream erosion by the Connecticut River, when the river eroded the 35 to 55 foot high, 25 to 40^0 wooded slope that separates the terrace from the present day Connecticut River. This terrace displays a variety of fluvial features formed by the river as it migrated across the ancient floodplain. These include fluvial scarps and adjacent depressions. The fluvial scarps and larger terrace escarpments are ancient analogies to the present day slopes of the Connecticut River. The depressions adjacent to these scarps and escarpments formed as scour channels or abandoned tributary streams on the floodplain. The depressions were subsequently partially filled as the stream migrated away from the channel.

The elevation of this terrace is about 255 to 275 feet National Geodetic Vertical Datum (NGVD),

BRATTLEBORO, VERMONT – NEW HAMPSHIRE

PROVISIONAL EDITION 1984

figure 22

UNCONSOLIDATED SURFICIAL DEPOSITS

Quaternary

- **m** — FILL or modified ground; not shown in site vicinity.
- **Qal** — RECENT ALLUVIUM - Fluvial sand, gravel and silt deposits underlying the present-day floodplains of the Connecticut River and tributary streams.
- **Qls** — LANDSLIDE DEPOSITS or scarps (Areas slightly exaggerated to show at map scale)
- **Qs** — SWAMPS, PEAT OR MUCK overlying shallow bedrock.
- **Qu** — POORLY DRAINED AREAS underlain by undifferentiated colluvium, alluvium and/or till over shallow bedrock.

LITTORAL GLACIOLACUSTRINE DEPOSITS:

- **QT1** — QT1 - Predominantly sandy underlying high terraces along the Connecticut River Valley;
- **QT2** — QT2 - Predominantly well-sorted sand and gravelly underlying intermediate terraces along Connecticut River Valley. Includes post-glacial fluvial sediments in Kilburn Brook;
- **QT3** — QT3 - Predominantly well-sorted sand and silty underlying low terraces along the Connecticut River Valley
- **Qc** — GLACIOLACUSTRINE BOTTOM SEDIMENTS consisting of varved silty clay, clay, and silt.

STRATIFIED METAMORPHIC ROCKS

- **Dl** (Lower Devonian) — LITTLETON FORMATION - Slate, phyllite and mica schist with interbedded quartzite; biotite, garnet, and staurolite porphyroblasts.
- **Sc** (Silurian) — CLOUGH QUARTZITE - Quartzite, muscovite schist, and quartz-pebble and quartzite-pebble conglomerate in a quartzite and quartz mica schist matrix.
- **Oa** (Ordovician) — AMMONOOSUC VOLCANICS - Well-foliated quartz-feldspar-biotite gneiss with thick interbeds of amphibolite; minor sulfidic muscovite-quartz schist; scattered lenses of breccia.

PLUTONIC ROCKS

- **NHg** (Middle Devonian) — NEW HAMPSHIRE PLUTONIC SERIES - Medium to coarse-grained, granite, granodiorite and quartz diorite; some bodies weakly to moderately foliated.
- **Ol** (Ordovician) — OLIVERIAN PLUTONIC SERIES - Medium to coarse-grained, sub-porphyritic granodiorite, quartz diorite and quartz monzonite gneiss; strongly to weakly foliated.

MAP SYMBOLS

- Location of Geologic Profile
- Approximate Contact
- Inferred Bedrock Contact Below Surficial Units
- 56 — Strike and Dip of Bedding (upright or direction of top unknown)
- 34 — Strike and Dip of Overturned Bedding
- 67 — Strike and Dip of Foliation
- Strike and Dip of Vertical Foliation
- 90 — Strike and Dip of Jointing

NOTES

1. Bedrock units typically are mantled by a veneer of woodland soil, colluvium, and glacial till.
2. See Figure 2.3-3 for Geologic Profile A-A'.
3. Base map from U.S. Geological Survey 1:25,000-scale metric topographic maps.
4. Geology based on reconnaissance mapping by Hanson, Shannon & Wilson, Inc. Bedrock mapping modified from Hepburn et. al. (1984) and Moore (1949).

N

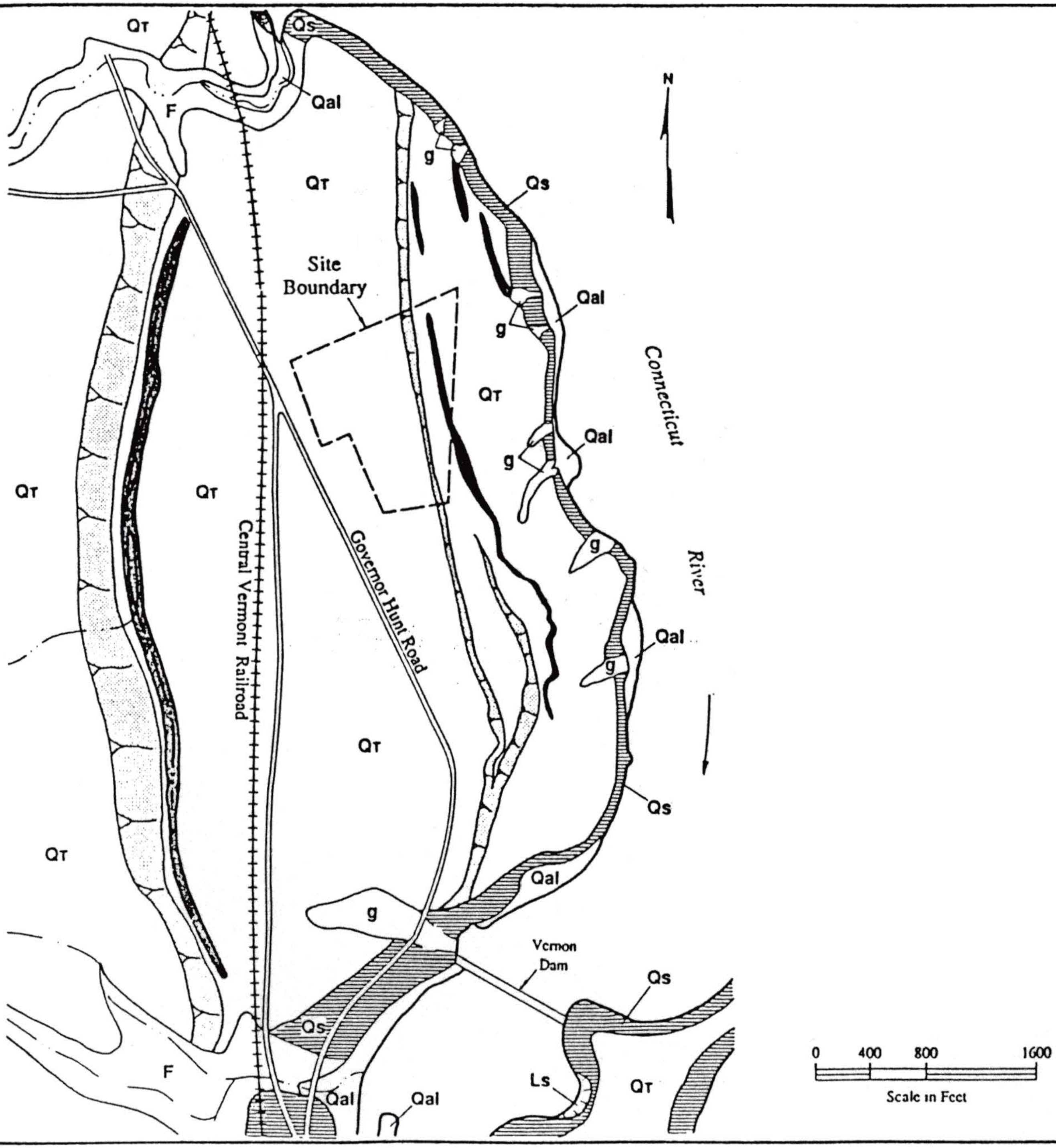
0 1/2 1

Scale in Miles

SITE AREA SURFICIAL GEOLOGY MAP

Figure 2.3-2

figure 23



EXPLANATIONS

DEPOSITIONAL LANDFORMS

Qal — Alluvial floodplain of the present-day Connecticut River and its tributaries.

QT — Gently undulatory fluvial terrace surfaces eroded in glaciolacustrine deposits. Originated during Holocene incision of the Connecticut River Valley.

EROSIONAL LANDFORMS

—·· — Intermittent stream

Ls — Landslide mass and scarp

g — Gullies developed along steep banks of the Connecticut River. Formed primarily by seepage flow and mass wasting.

F — Moderately steep slopes and channels eroded by present-day intermittent streams.

Qs — Steep slopes bordering the present-day Connecticut River and floodplain.

Uniform breaks in slope on the terrace surfaces; formed as ancient terrace escarpments and natural levees. Originated during Holocene incision of the Connecticut River Valley glaciolacustrine fill.

Elongate,closed depressions on the terrace surfaces; formed by channel scour, abandoned tributaries, or abandoned meander bends. Originated during Holocene incision of the Connecticut River Valley glaciolacustrine fill.

NOTES

1. Map depicts landforms prior to cut and fill associated with construction of the Vermont Yankee Nuclear Power Station. See Figure 2.3-7 for distribution of the fill materials in the immediate site vicinity.

2. Contacts between landform units are approximate. Small gullies are exaggerated slightly to portray at this map scale.

3. Distribution of map units is based on field maping and topographic map and aerial photo interpretation.

4. Topographic base maps used include U.S.G.S. Brattleboro Quadrangle (7.5 minute), and topographic plans of the Vermont Yankee site vicinity by Webster-Martin, Inc. (1965) and Eastern Topographics (1989).

GEOLOGIC LANDFORM MAP
VERNON VERMONT SITE VICINITY

Figure 2.3-1

figure 24

and 35 to 55 feet above the maximum pool elevation of the River (Hanson, 1991). Locally, this terrace is about 3,500 feet wide and has a gently undulatory surface of broad, north-trending swells and swales which have amplitudes of a few feet. The terrace slopes gently away from the river to the west. However, there are several curvilinear fluvial scarps which roughly parallel and step downward towards the river in five to ten foot increments. Depressions at the base of these small scarps accentuates the local relief. The most pronounced depression is at the base of the escarpment separating the lowest main terrace from the intermediate level terrace to the west. This low area ponds seasonally from groundwater discharge and from an intermittent drainage channel that flows into it from a small drainage basin in the next higher terrace to the west. Water may pond in this area despite the coarseness of the sediment of the site due to soil development, windblown fines deposited in the depression, and subsequent deposition of organic material by plant growth. Another fluvial scarp and abandoned channel trends northward through the eastern portion of the site where it has a local relief of as much as 18 feet. This scarp has been partially modified within the site by excavation and filling, prior to the construction of Vermont Yankee. Land modification in this area consisted of excavation along the west side of the scarp and subsequent filling to a lower elevation, leaving a narrow ridge bounded on the east by a relatively unaltered slope and on the west by an excavated slope.

Several gullies have developed in the site vicinity along the bluff overlooking the Connecticut River. The gullies formed due to seepage erosion, and mass wasting. Hanson (1991) noted that many gullies directly north and northeast of the site occur in areas where depressions (swales) in the original terrace surface intersect the top of the bluff. The largest gully is located south of the site near Vernon Dam. The gully was formed by groundwater discharge derived from the drainage area above the lowest terrace and nearby recharge in a surface depression along the western edge of the terrace. In the area now occupied by the Vermont Yankee Nuclear Power Station, Hanson (1991) believed these gullies to be formed by seepage erosion. Seepage was theorized to be increased in this area due to concentration of groundwater flow due to the shallowness of the bedrock in this area and the channelized nature of the surface of the relatively impervious bedrock.

Drainage

Very little drainage development has occurred on the lower terrace where the site is located. This is due to the relatively young age of the terrace as well as the relatively high permeability of the fluvial and glacio-lacustrine sediments underlying the terrace. Precipitation directly infiltrates into the ground resulting in minimal surface flow. The undulatory surface and closed depressions in the terrace surface, tends to trap surface runoff and allows it to infiltrate across a relatively wide area. This lack of flow is demonstrated at the western edge of the terrace, where an intermittent stream that originates further upslope flows onto the lowest terrace. This stream channel is relatively well developed on the higher slope, but becomes a losing stream where it enters the ponded curvilinear depression on the edge of the lowest terrace. The surface flow from this stream spreads out into the closed depression and infiltrates into the ground. An on site visit confirmed this and streams running on bedrock channels where seen to run dry upon reaching the sandy glacio-lacustrine and fluvial deposits of the meander scar.

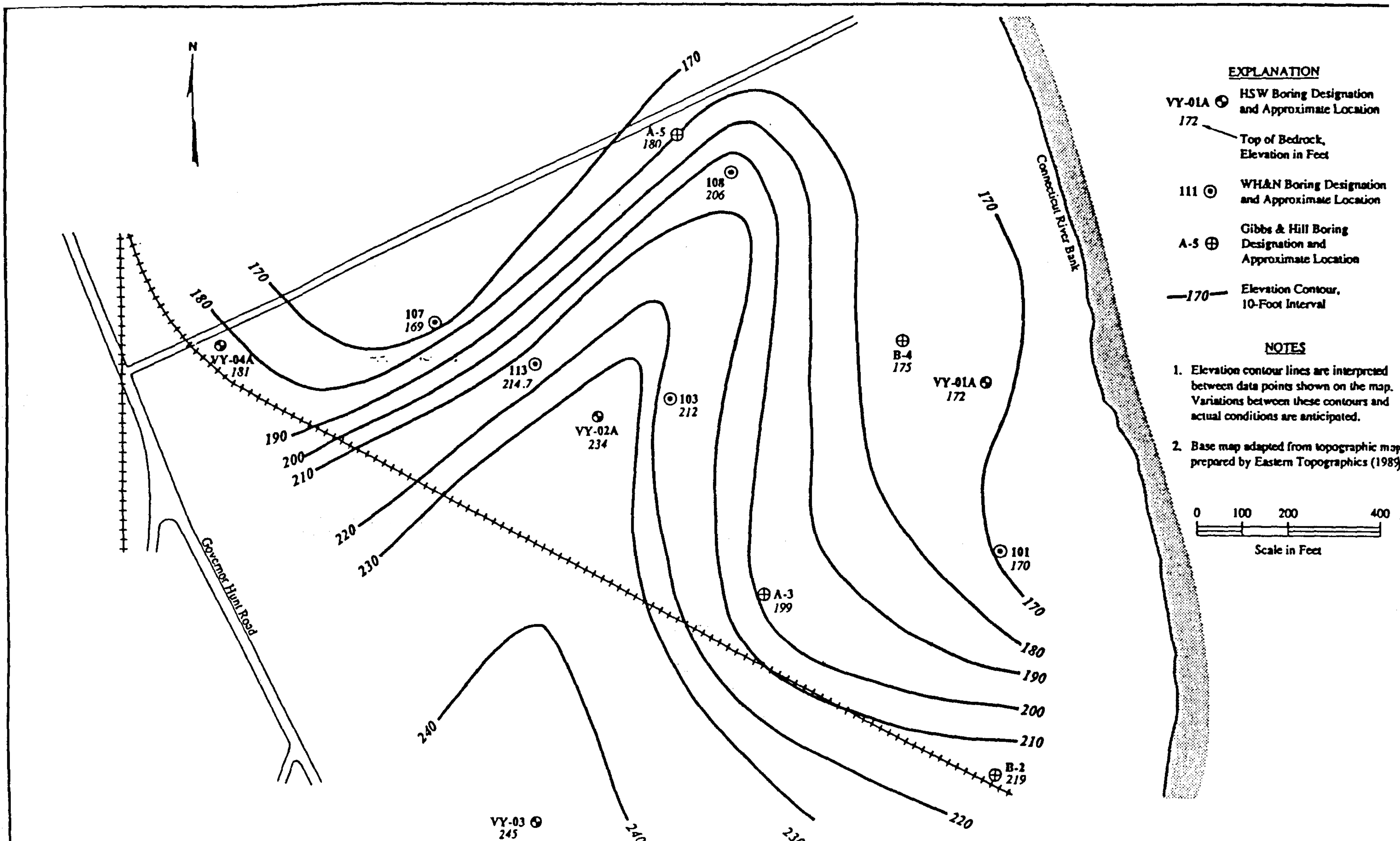
Bedrock Geology

The site and surrounding area consists of the Oliverian Plutonic Series, the New Hampshire Plutonic Series, and the formations of the Eastern Sequence, which have previously been discussed. The depth to bedrock at the site varies considerably as the erosional surface of the bedrock has a local relief of at least 60 feet (Hanson, 1991). Hanson (1991) developed a contour map of the top of the bedrock, and an isopach map of unconsolidated sediments. Hanson's contour map shows that the bedrock surface beneath the site forms a distinct north-trending ridge, with north to northeast trending buried depressions to the east and west (see figure 25). The depth to bedrock shown in Hanson's Isopach Map of Unconsolidated Sediments (see figure 26), increases from less than 30 feet at VY-03 in the southwestern area of the site to 90 feet at VY-04 in the northwestern part of the site. Depth increases to the east, where around VY-01 the depth to bedrock is 84 feet. In the southwest area of the site, in the vicinity of the Vermont Yankee Nuclear Power Station, rock exposed along the river is 30-40 feet below the site elevation. Approximately 1,300 feet to the north of the site, the depth is 140 feet. Battelle's figures confirm these results, showing that depth to bedrock varies between 47 and 90 feet over the site.

The top of the bedrock, as observed in borings and exposures of granitic gneiss below Quaternary soil units in the site area, is typically unweathered to very slightly weathered and locally striated with glacial grooves. This suggests that the relief is due to Pleistocene glacial scour, and pre-glacial erosion of the Connecticut River Valley.

Although the bedrock underlying the site is intensely deformed, very few faults have been observed. This is because Paleozoic deformation was mostly ductile and resulted in complex folding in response to east-west compressional stress. East-west rifting during the Mesozoic created some faults such as the Triassic Border Fault, along the east side of the Connecticut Valley in Massachusetts and Connecticut. The fault is about 6 miles southeast of the site at its closest point. A small fault about 4.5 miles north-northeast of the site strikes N20°E. This fault displaces the Oliverian Plutonic Series, and overlying Ammonoosuc, Clough and Littleton Formations and has about 600 feet of displacement down and to the east. This fault is probably post-metamorphic and occurred due to Mesozoic rifting.

WHN (1988) noted fracture traces and a possible shear zone in the vicinity of the site. These fracture traces appear as darkened linear trends in soils exposed in fields. The most pronounced is a



CONTOUR MAP OF TOP OF BEDROCK

Figure 2.3-6

figure 25

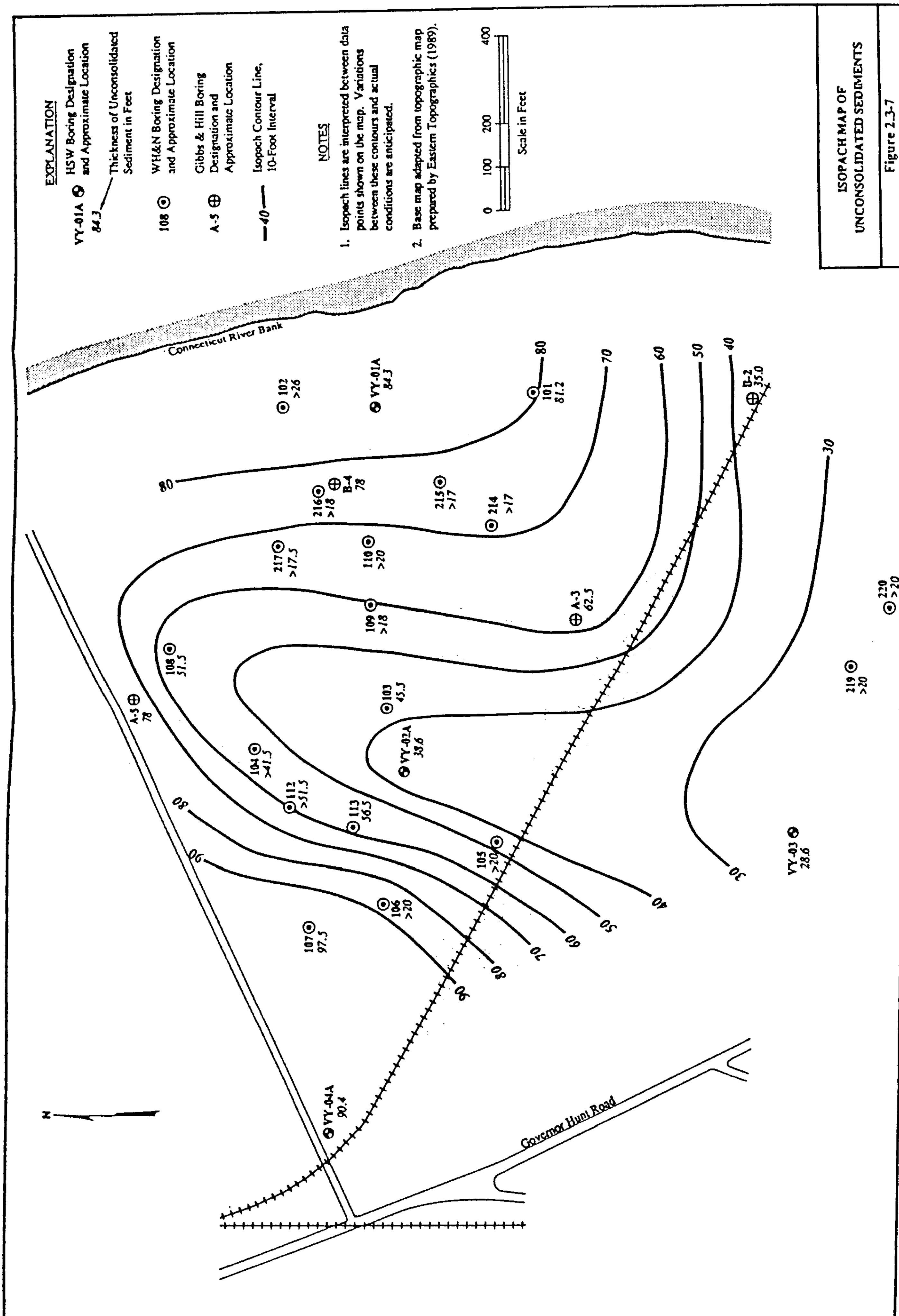

EXPLANATION
VY-01A 84.3 HSW Boring Designation and Approximate Location
Thickness of Unconsolidated Sediment in Feet
108 WH&N Boring Designation and Approximate Location
A-5 Gibbs & Hill Boring Designation and Approximate Location
40 Isopach Contour Line, 10-Foot Interval
NOTES
1. Isopach lines are interpreted between data points shown on the map. Variations between these contours and actual conditions are anticipated.
2. Base map adapted from topographic map prepared by Eastern Topographics (1989).
0 100 200 400
Scale in Feet
ISOPACH MAP OF UNCONSOLIDATED SEDIMENTS
Figure 2.3-7
Connecticut River Bank
Governor Hunt Road
N

figure 26

zone trends N45°W just upstream of Vernon Dam. This zone trends northwest of the dam for about 1,500 feet. Several other photolineaments trend north-northwest in the vicinity of the site. One weak lineament parallels the general trend of the buried bedrock topography at the site, and coincides with the steep drop in bedrock between VY-02 and VY-04.

The surface of the bedrock underlying the site is closely to very closely jointed and is locally intensely fractured (Hanson, 1991). Fractures and joints are usually iron stained near the surface and are commonly filled by chlorite, calcite or clay minerals at depth. The strongest joint sets strike N10-20°W, and dips about vertically. A second set strikes N45-55°E, and dips steeply north. A bedrock aquifer test by WHN (1988), indicated the bedrock fractures and joints are hydrologically connected to the overlying Quaternary sediments.

Surficial Geology

The sediments underlying the site consist of glacio-fluvial and glacio-lacustrine sediments (see figures 15, 23,24). These sediments were mostly deposited in Lake Hitchcock. Because of the process of shoaling in Lake Hitchcock, grain size in the sediments of the Connecticut River Valley increases with elevation. The oldest and stratigraphically lowest deposits are varved clay, laminated silty clay and clayey silt with thin interbeds of fine to very fine sand. These sediments are exposed on river banks just below Vernon Dam, and have been observed in some borings for Vermont Yankee (Hanson, 1991). These sediments were deposited in the bottom of the lake. Higher in the sequence, the sediments underlying the lowest terrace cut in the glacio-lacustrine deposits consists predominately of silt and sand with some gravels, whereas coarse sand and gravel are progressively more abundant in the intermediate and upper terraces.

Fluvial deposits of variable thickness mantle the glacio-lacustrine sediments on the terraces. The fluvial sediments were deposited by the Connecticut River as it downcut through the glacio-lacustrine sediments and meandered back and forth across the valley. Fluvial sediment is difficult to distinguish from lake deposits, although they are generally finer grained than glacio-lacustrine deposits on the upper terraces and coarser than those on the lowest terrace.

Alluvium is the youngest Quaternary deposit in the area. Alluvium underlies the present floodplain of the Connecticut River and its larger tributaries. Alluvium underlies areas of the riverbank to the east of the site, and probably extends below the river. The alluvium consists of loose to medium dense silts and sands which have been deposited as broad lowlands and islands along the river.

As already noted, the surrounding highlands are covered by till. Hanson (1991) identified a diamicton at the site (Unit E) which resembles ablation tills and may correlate with them.

Hanson (1991), differentiated five units in the sediments directly underlying the site. The units were identified from stratigraphic and lithologic studies of test pits and borings drilled by Hanson Engineers in 1991 and supplemented by borings by WHN 1988, 1989. From oldest to youngest these units are: Unit E, Unit D, Unit C, Unit B, and Unit A. Unit E is a diamicton sediment, that consists of very dense, silty, gravelly sand to sandy gravel. Unit D is a glacio-lacustrine sediment that consists of a dense to very dense, fine sand and silty fine sand. Unit C is a glacio-lacustrine sediment that consists of a loose to dense silt and fine sandy silt. Unit B is a glacio-lacustrine/glacio-fluvial sediment that consists of medium dense sand and gravelly sand. Unit A is a glacio-fluvial sediment that consists of a loose fine sand, sandy silt, and silty sand.

During an on site visit (July 1-3, 1991) a gravel pit 2,500 feet west of VY-04 or the western most point of the proposed repository site (marked by star on figure 22) and a smaller gravel pit on the Miller Farm, also west of the site were studied. The larger gravel pit showed stratified deposits varying from fine silt to cobble layers (see figure 27). This is most likely a kame, kame terrace or the

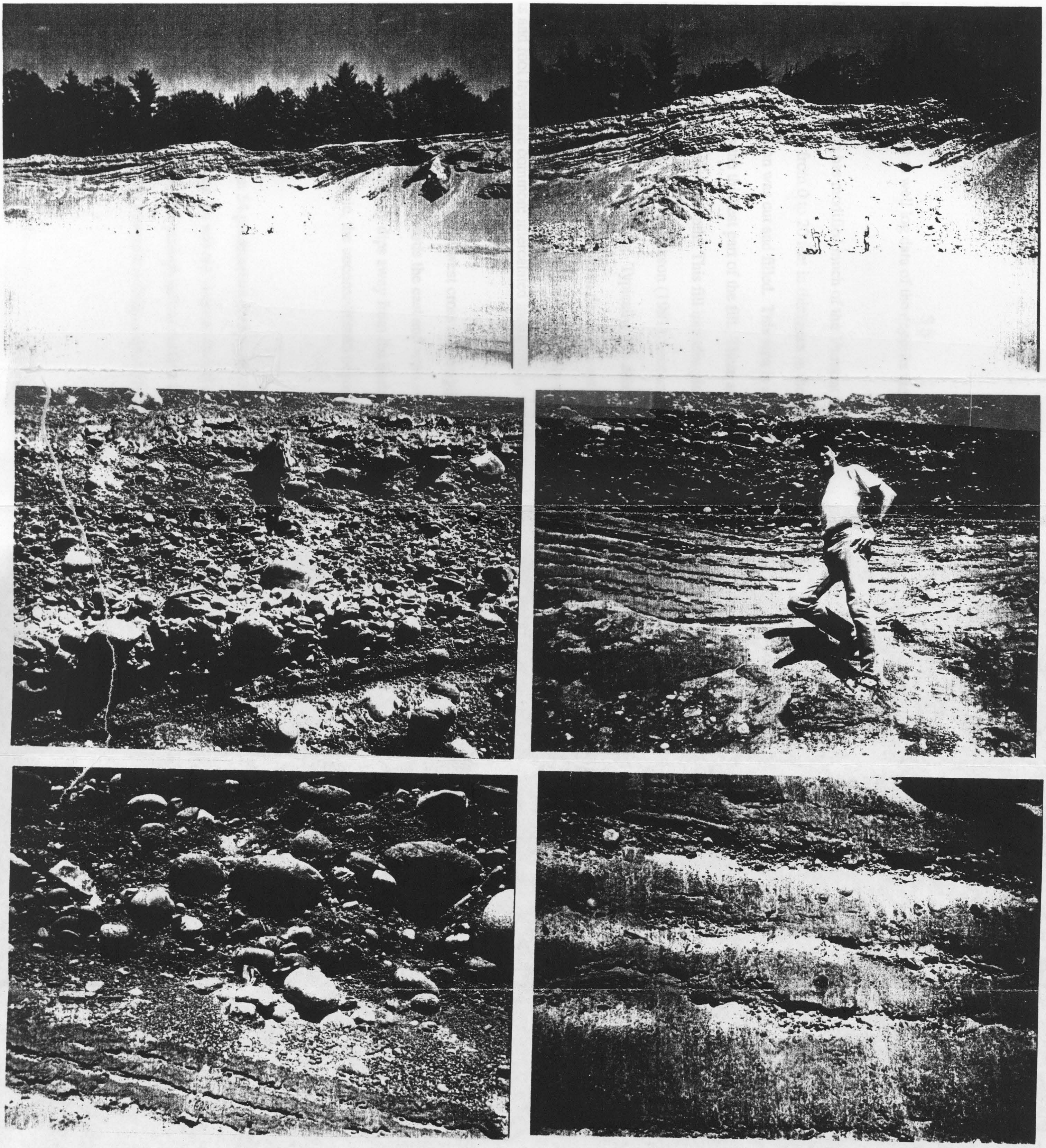


figure 27

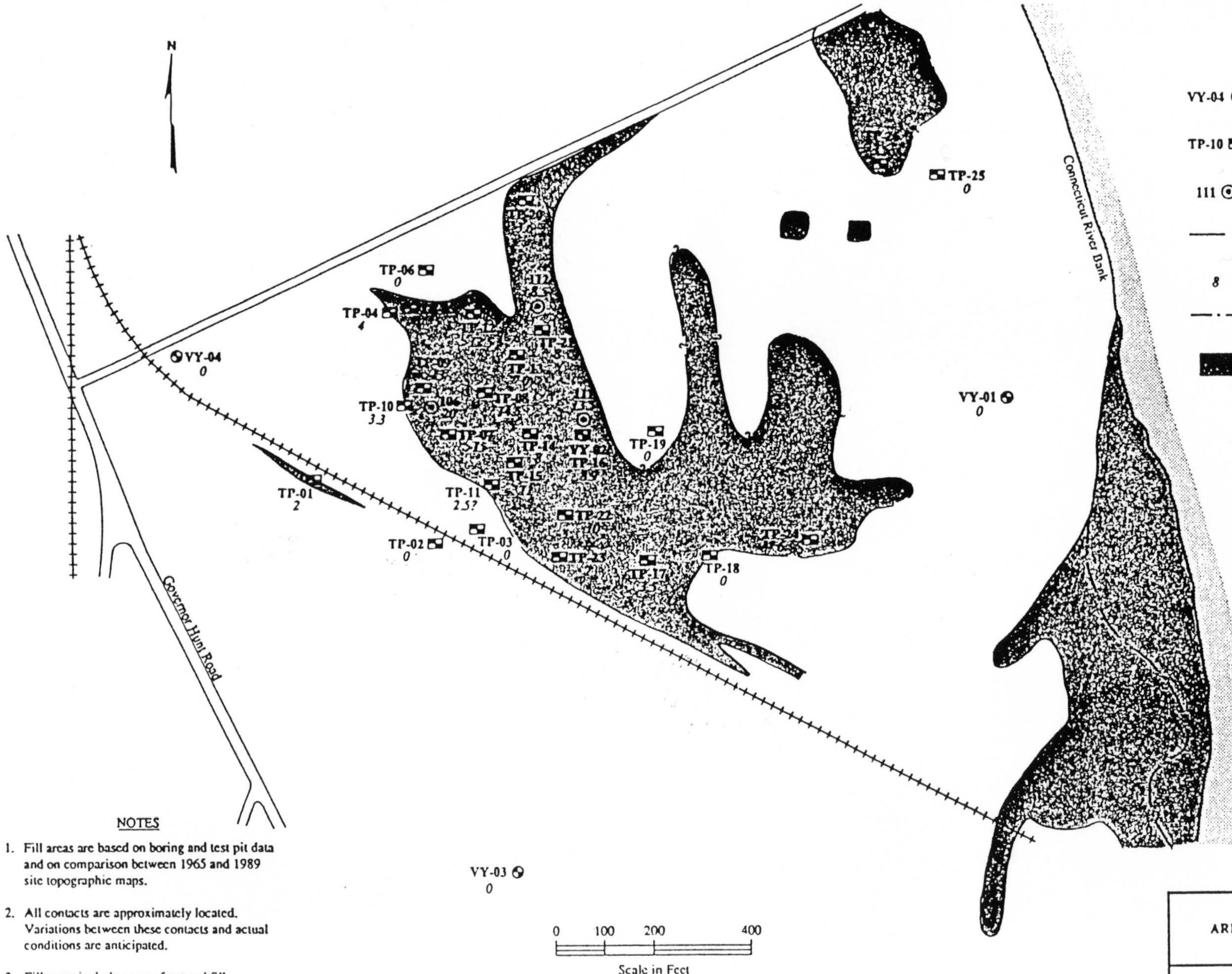
topset beds of a delta. These deposits are very similar to well log data of the deposits that underlie the site.

Fill is also an important sediment as construction has modified much of the Vermont Yankee property with cut and fill (see figure 28). Fill varies from 0 to 20 feet in thickness in the area of MW-106. In the MW-106 area, a relatively deep excavation was cut and filled. This area is adjacent to a tree covered debris slope which probably delineates the thickest part of the fill. There are two types of fill: debris fill and soil fill. Debris fill typically occurs at depth. This fill includes plastic sheeting, rebar, glass, wooden planks, and concrete. In several test pits, Hanson (1991), encountered this debris at depths of 12 to 16 feet and noted it formed a discrete layer. Typically, this debris horizon was at the watertable. The soil fill generally consists of loose to medium dense fine sandy silt and silty fine to medium sand, with traces of gravel and boulders. The texture is generally massive to mottled. Locally, root fragments and root layers are common; intercalated inclusions of very dense, very dark grayish brown, fine sandy silt are rare to abundant.

All these units vary in their thicknesses across the site. An east-west cross section prepared by Hanson (1991)(see figure 29) shows that sediments thicken towards the east and west away from a bedrock high. The contacts between the deeper units generally dips away from the bedrock high, with the dip decreasing to the shallower contacts. As a whole, the unconsolidated deposits vary in thickness from 17.3 feet to 87.1 feet.

Hydrographs

Data was collected from April to September 1991 from 54 piezometers completed at different depths over the site (see figure 30). Since the sediments on the site are unconsolidated and lack any confining layers, the aquifer is predominately unconfined. The potentiometric surface thus conforms to the surface topography of the site. The water table slopes toward the Connecticut River to the east.



EXPLANATION

VY-04 HSW Boring Designation and Approximate Location

TP-10 HSW Test Pit Designation and Approximate Location

111 WH&N Boring Designation and Approximate Location

Approximate Edge of Fill; Queried where Inferred

8 Fill Thickness in Feet

Pre-Fill Connecticut River Shoreline

Fill

NOTES

1. Fill areas are based on boring and test pit data and on comparison between 1965 and 1989 site topographic maps.

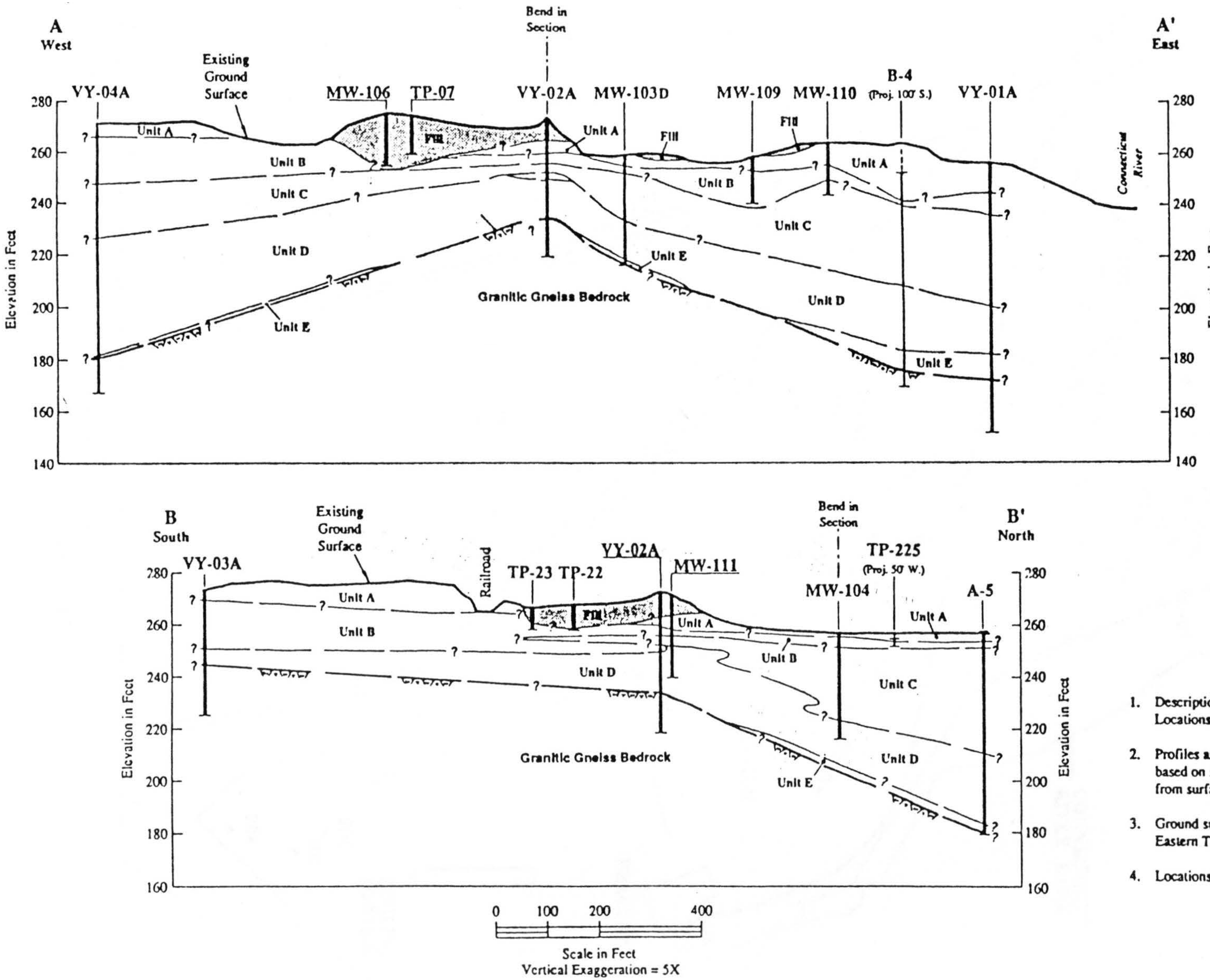
2. All contacts are approximately located. Variations between these contacts and actual conditions are anticipated.

3. Fill areas include areas of cut and fill.

AREAL DISTRIBUTION OF FILL

Figure 2.3-4

figure 28



LEGEND

VY-01A ← Boring,
TP-07 ← Test Pit and
MW-106 ← Monitoring Well Designation and Approximate Location

? Approximate Geologic Contact

← Bottom of Boring

Fill — Predominantly loose to medium dense, sandy SILT with scattered cobbles, wood debris, and construction debris.

Unit A Loose to medium dense, fine sandy SILT to silty fine SAND.

Unit B Medium dense to dense, clean to silty, gravelly SAND to sandy GRAVEL with frequent iron-/manganese-oxide stained layers.

Unit C Predominantly loose to dense SILT to fine sandy SILT with interbeds of silty fine SAND and occasional thin clay layers.

Unit D Predominantly dense to very dense, silty fine SAND with interbeds of fine SAND and sandy SILT.

Unit E Very dense, silty gravelly SAND with scattered to frequent cobbles and boulders.

NOTES

1. Descriptions of geologic units are presented in Section 1.4-2. Locations of profiles are shown on Figure 2.3-4.
2. Profiles are based on boring and test pit data. Contacts are interpreted based on stratigraphic correlation between borings and test pits, and from surface contour maps, and are approximate.
3. Ground surface data obtained from topographic map prepared by Eastern Topographics, 1989.
4. Locations of WH&N and Gibbs & Hill explorations are approximate.

GENERALIZED SUBSURFACE PROFILES A-A' AND B-B'

Figure 2.3-5

figure 29

*see isopach map for location of profile

PIEZOMETER LOCATION MAP

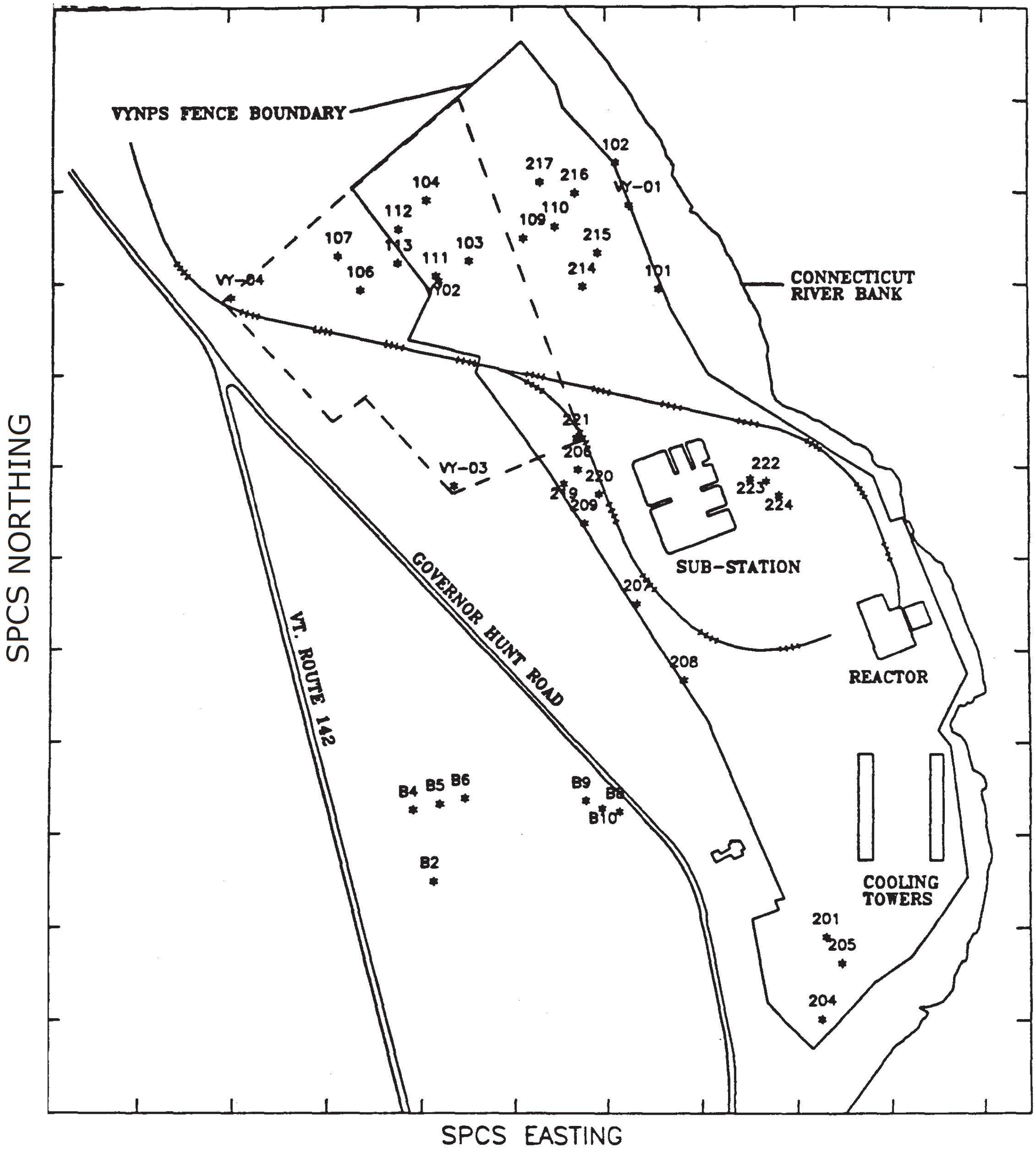


figure 30

The water levels in the river are generally at 218 -220 feet. Hydrographs (see figures 30.1-30.19) show a general decline in water levels from Spring to Fall, due to increased heat and evapotranspirtation during summer. Hurricane Bob, which hit the coast August 18-19, is the cause of the pronounced recharge event in the August 15 - 29 period. Increases in water levels in deeper wells while shallow wells have decreasing water levels may indicate a slug of water moving downwards through the unconsolidated deposits. For example, see the April to May readings for the 104 well cluster. However, most hydrographs show a close correlation between changes in water levels in deep and shallow wells. For example, see the 107 well cluster, wells 222-223-224, wells 219-220-206-221, the 103 well cluster, and the 113 well cluster. Most hydrographs (101, 107, 222-223-224, 219-220-206-221, 103, 104, 112, 113, 106-113S-111, VY02, VY03) show a downward flow, as hydraulic head values are higher in shallower piezometers than deep ones. This is because unconsolidated deposits are 20 to 40 feet above the river discharge point, and shallow water will move down under the influence of gravity.

Several points on the hydrographs which do not fit the general trend described above are most likely erroneous or the result of faulty readings or improperly installed wells. Researchers at WHN believed that well 204 has not given accurate readings as data from WHN gave this well the exact same water level over the entire study period, the well being dry. The May 9 reading for well B2 and the May 23 reading of well VY-01A and VY-04A are believed to be inaccurate due to the recency of well installation. Re-estimation of well elevations or local pumping may have also varied readings.

Flow

The potentiometric surface for the shallow and unconsolidated sediments shows flow towards the Connecticut River (see figure 31). The gradient is less steep away from the river and increases near the river. This is most likely due to the topography of the site which slopes gently to the river over

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
101 WELL CLUSTER

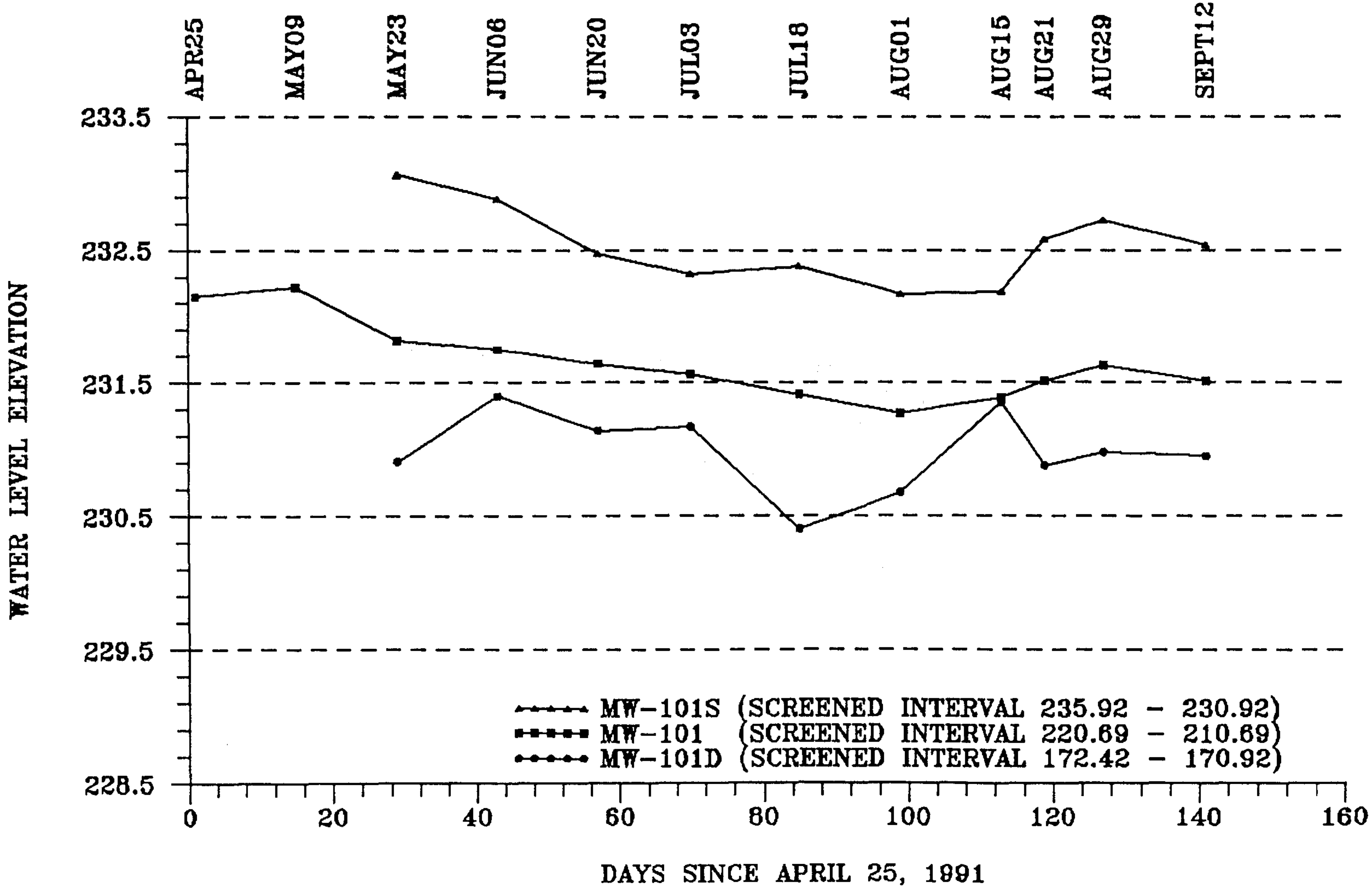
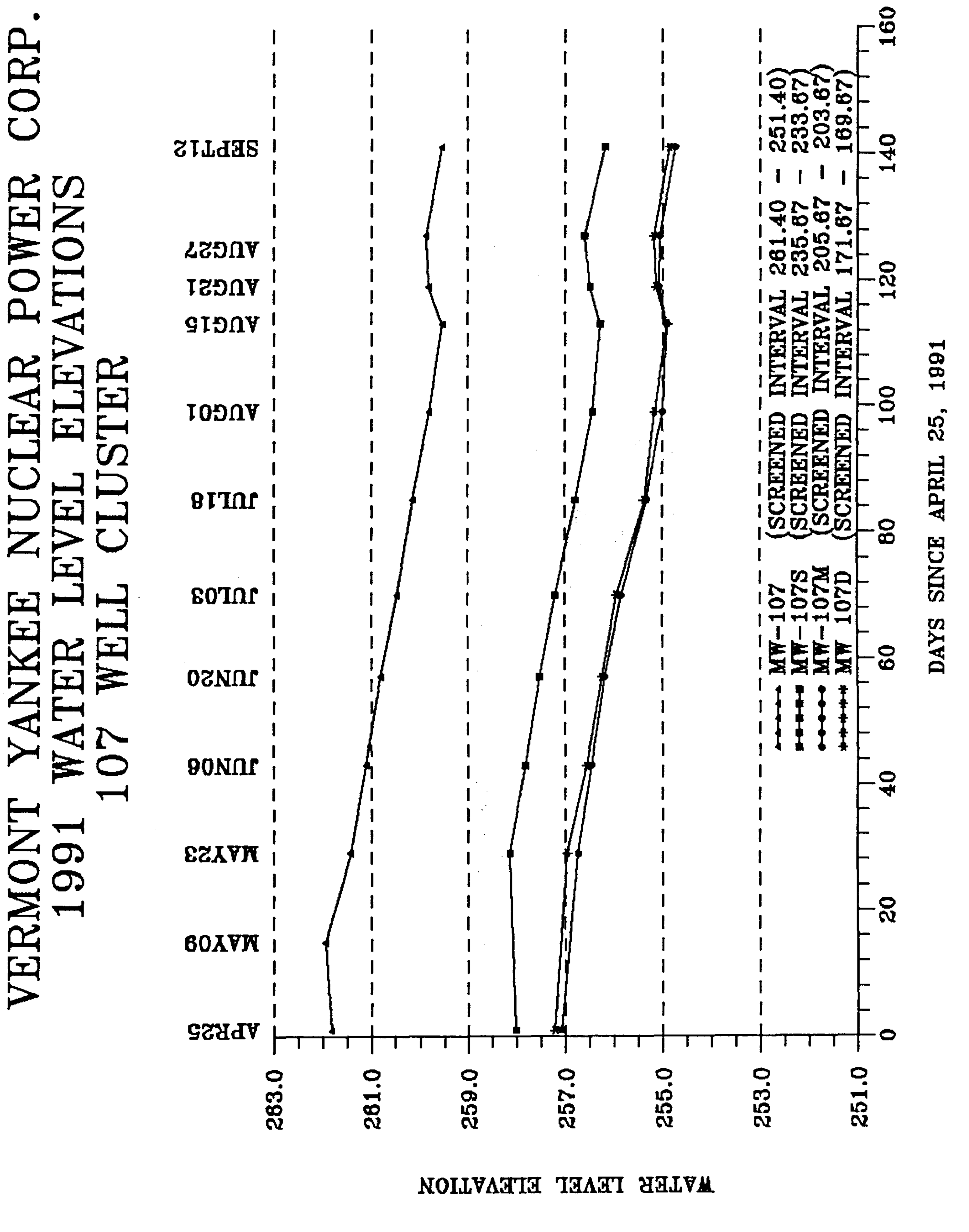


figure 30.1



VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
107 WELL CLUSTER
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG27
SEPT12
283.0
261.0
259.0
257.0
255.0
253.0
251.0
WATER LEVEL ELEVATION
MW-107 (SCREENED INTERVAL 261.40 - 251.40)
MW-107S (SCREENED INTERVAL 235.67 - 233.67)
MW-107M (SCREENED INTERVAL 205.67 - 203.67)
MW 107D (SCREENED INTERVAL 171.67 - 169.67)
0
20
40
60
80
100
120
140
160
DAYS SINCE APRIL 25, 1991

figure 30.2

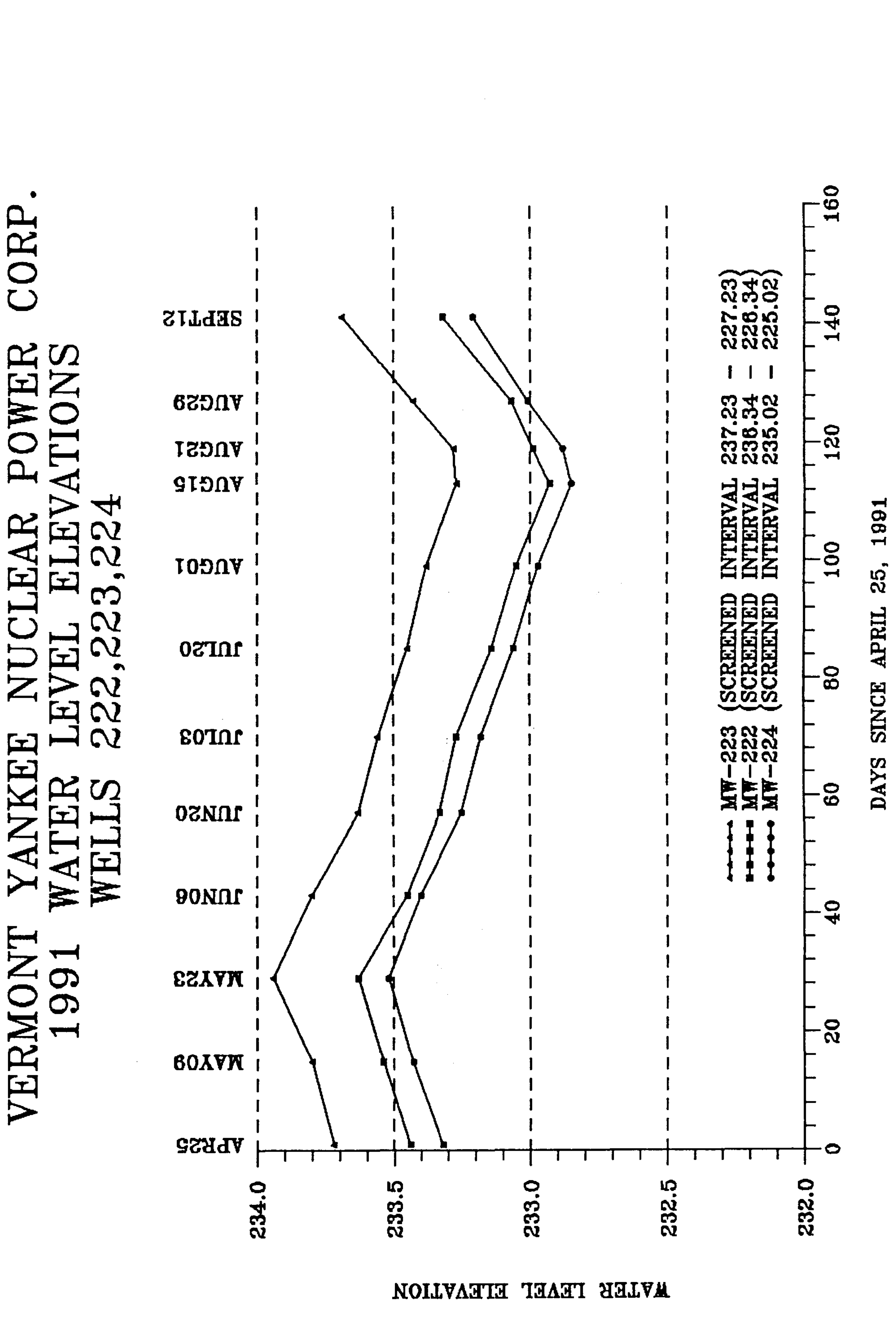
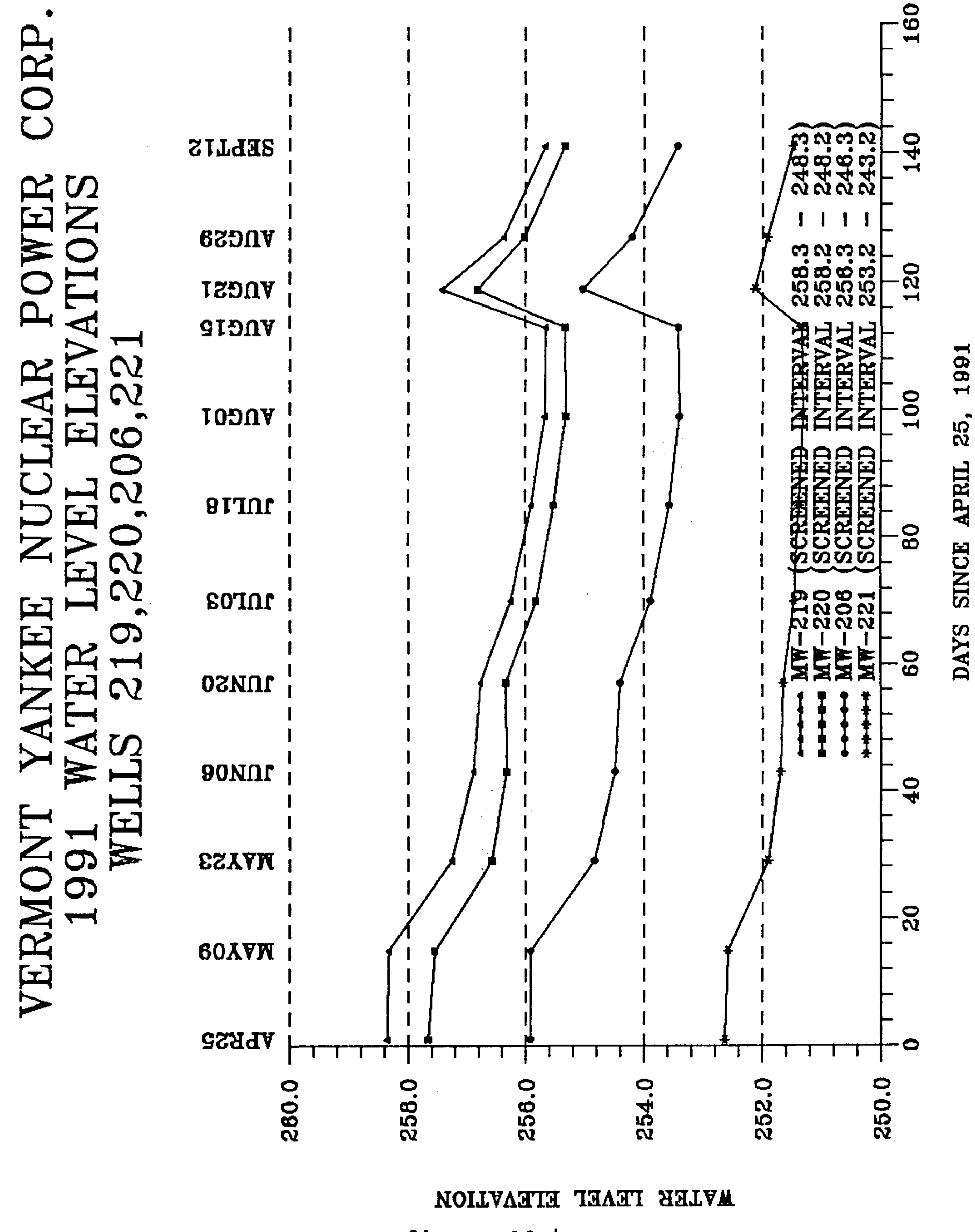

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
WELLS 222,223,224
WATER LEVEL ELEVATION
234.0
233.5
233.0
232.5
232.0
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL20
AUG01
AUG15
AUG21
AUG29
SEPT12
0
20
40
60
80
100
120
140
160
DAYS SINCE APRIL 25, 1991
MW-223 (SCREENED INTERVAL 237.23 - 227.23)
MW-222 (SCREENED INTERVAL 238.34 - 228.34)
MW-224 (SCREENED INTERVAL 235.02 - 225.02)

figure 30.3



VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
WELLS 219,220,206,221
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
MW-219 (SCREENED INTERVAL 258.3 — 248.3)
MW-220 (SCREENED INTERVAL 258.2 — 248.2)
MW-206 (SCREENED INTERVAL 256.3 — 246.3)
MW-221 (SCREENED INTERVAL 253.2 — 243.2)
WATER LEVEL ELEVATION
DAYS SINCE APRIL 25, 1991

figure 30.4

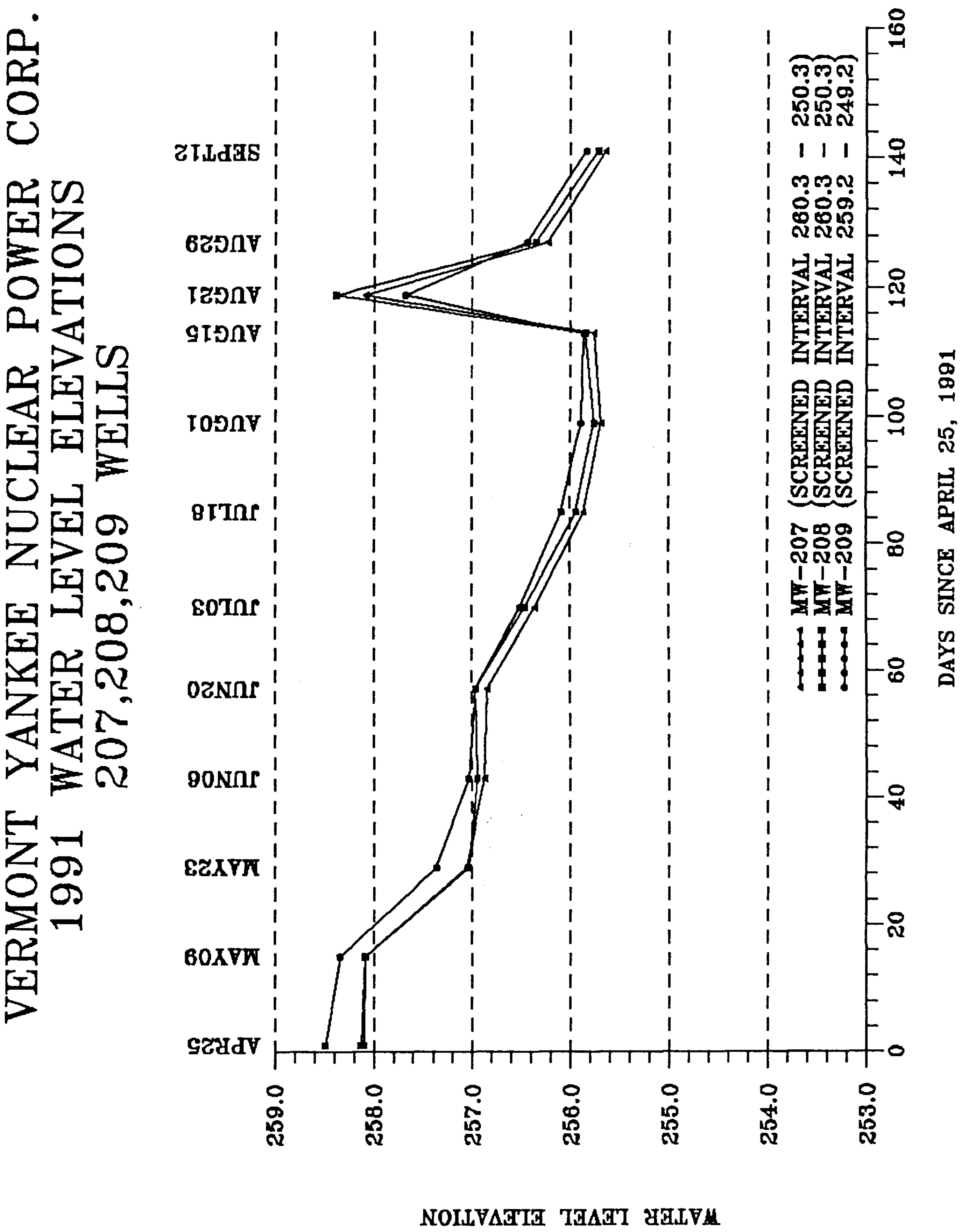

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
207,208,209 WELLS
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
259.0
258.0
257.0
256.0
255.0
254.0
253.0
0
20
40
60
80
100
120
140
160
MW-207 (SCREENED INTERVAL 260.3 – 250.3)
MW-208 (SCREENED INTERVAL 260.3 – 250.3)
MW-209 (SCREENED INTERVAL 259.2 – 249.2)
DAYS SINCE APRIL 25, 1991
WATER LEVEL ELEVATION

figure 30.5

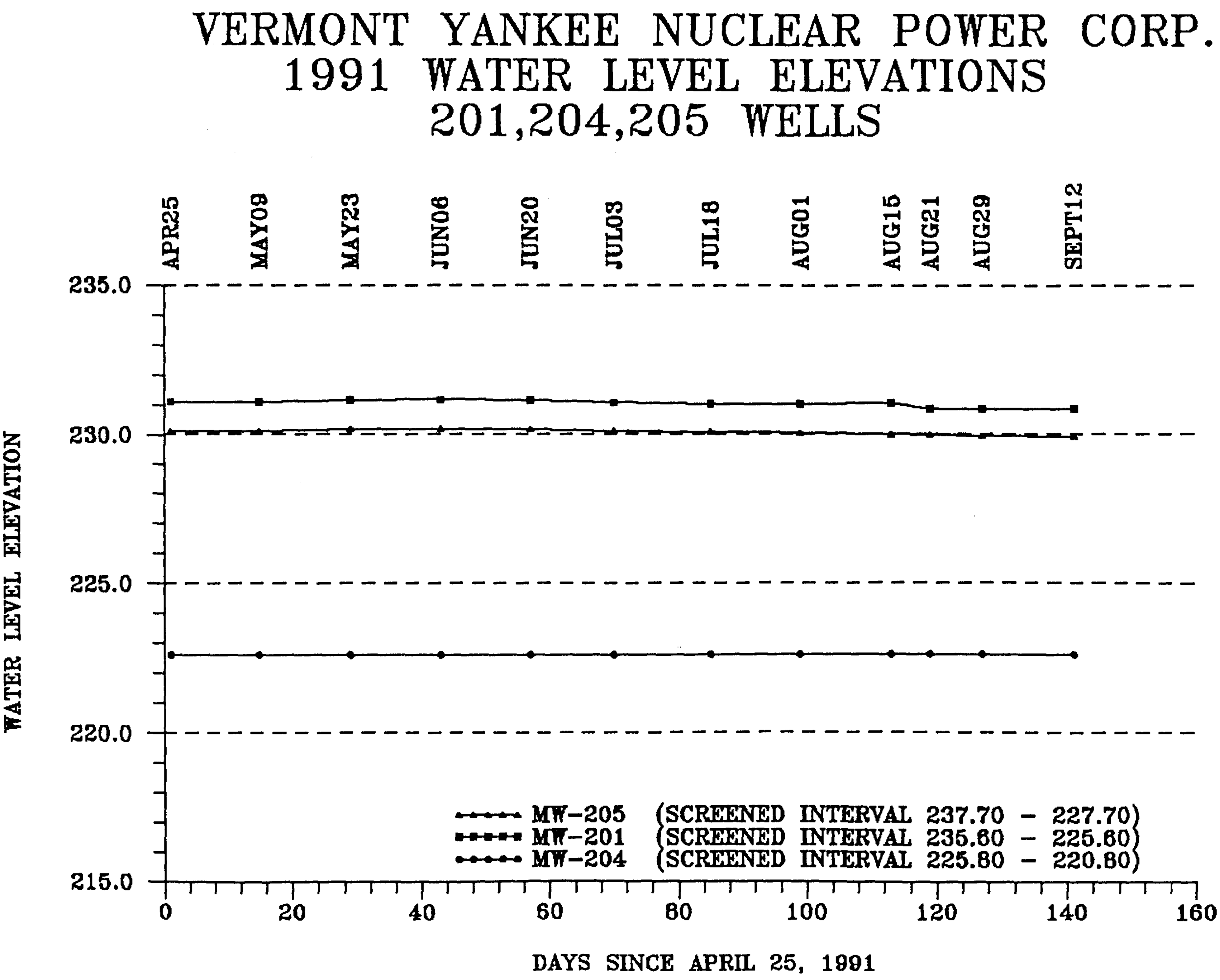

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
201,204,205 WELLS
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
235.0
230.0
225.0
220.0
215.0
WATER LEVEL ELEVATION
0
20
40
60
80
100
120
140
160
DAYS SINCE APRIL 25, 1991
MW-205 (SCREENED INTERVAL 237.70 - 227.70)
MW-201 (SCREENED INTERVAL 235.60 - 225.60)
MW-204 (SCREENED INTERVAL 225.80 - 220.80)

figure 30.6

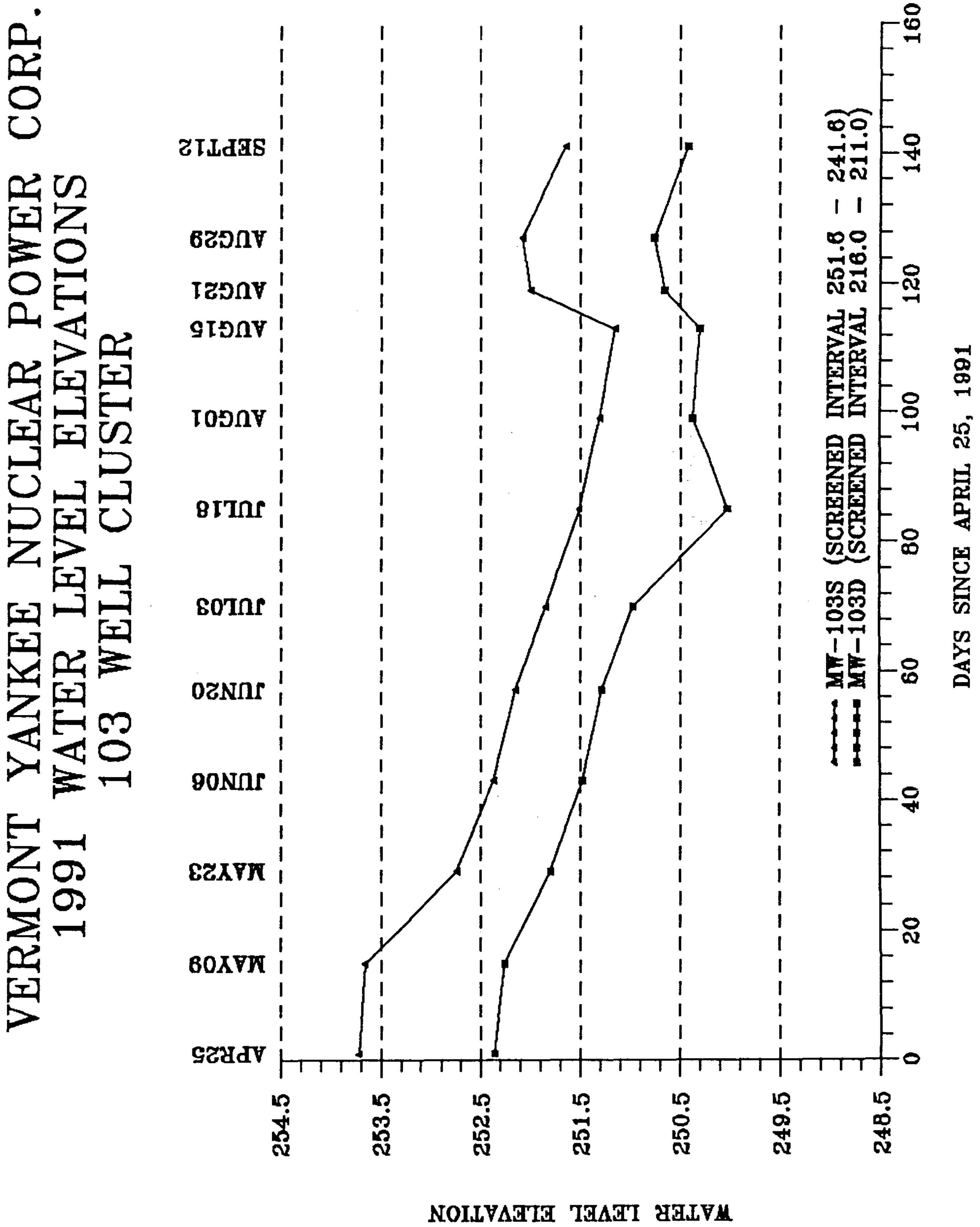

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
103 WELL CLUSTER
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
MW-103S (SCREENED INTERVAL 251.6 - 241.6)
MW-103D (SCREENED INTERVAL 216.0 - 211.0)
DAYS SINCE APRIL 25, 1991
WATER LEVEL ELEVATION
254.5
253.5
252.5
251.5
250.5
249.5
248.5
0
20
40
60
80
100
120
140
160

figure 30.7

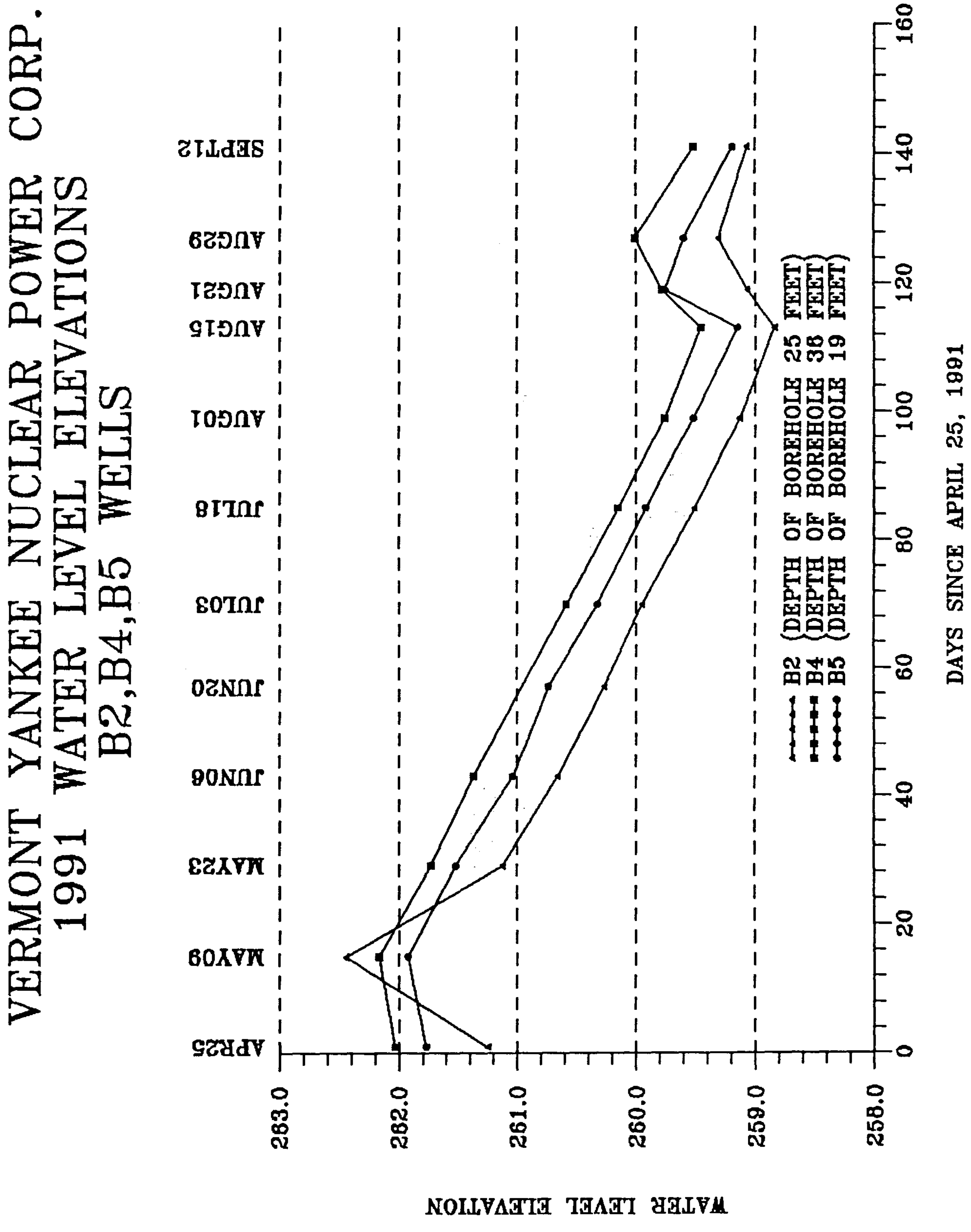

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
B2,B4,B5 WELLS
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
283.0
282.0
281.0
280.0
259.0
258.0
0
20
40
60
80
100
120
140
160
B2 (DEPTH OF BOREHOLE 25 FEET)
B4 (DEPTH OF BOREHOLE 38 FEET)
B5 (DEPTH OF BOREHOLE 19 FEET)
DAYS SINCE APRIL 25, 1991
WATER LEVEL ELEVATION

figure 30.8

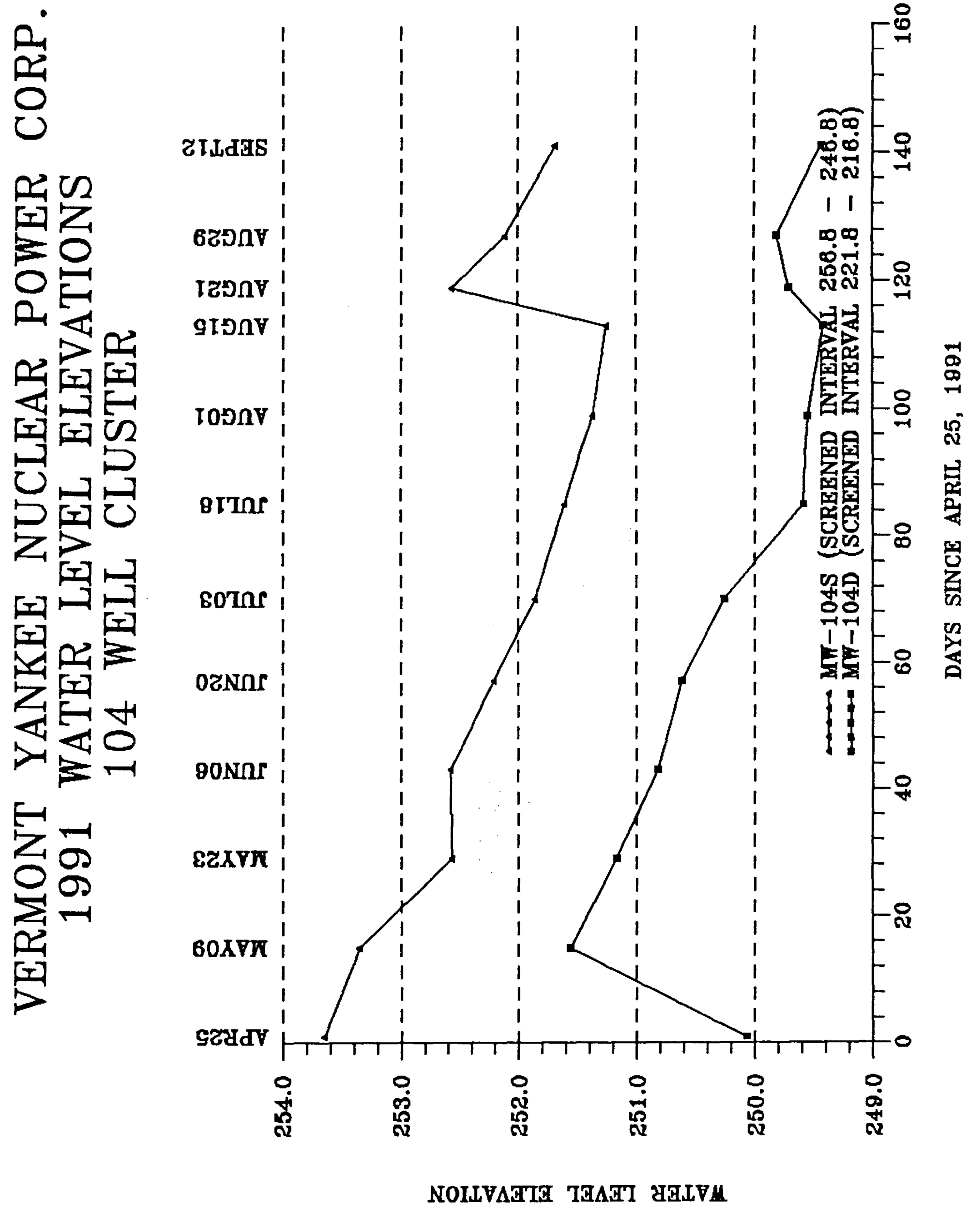

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
104 WELL CLUSTER
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
254.0
253.0
252.0
251.0
250.0
249.0
WATER LEVEL ELEVATION
0
20
40
60
80
100
120
140
160
DAYS SINCE APRIL 25, 1991
MW-104S (SCREENED INTERVAL 256.8 - 246.8)
MW-104D (SCREENED INTERVAL 221.8 - 216.8)

figure 30.9

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
112 WELL CLUSTER

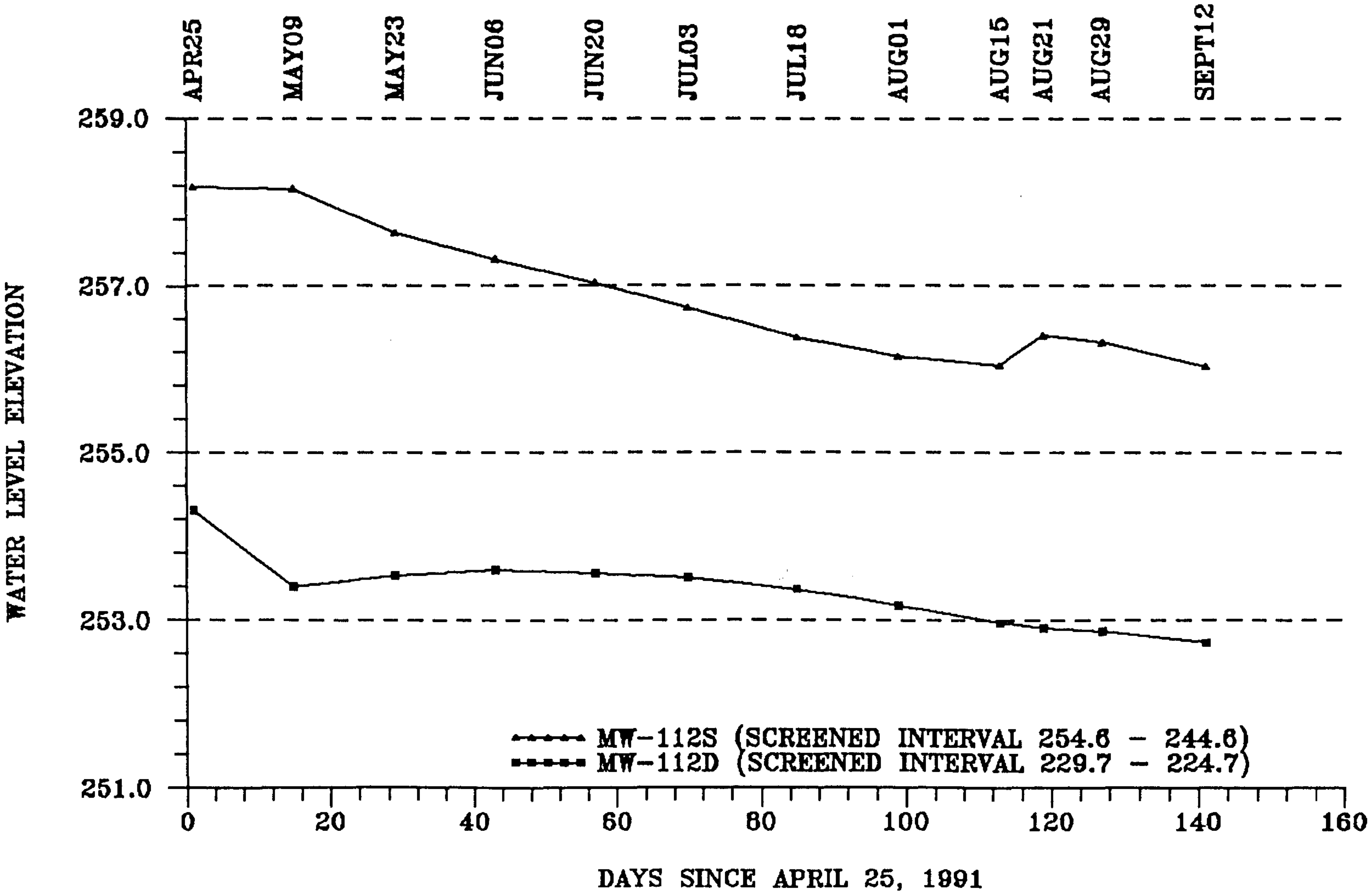


figure 30.10

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
113 WELL CLUSTER

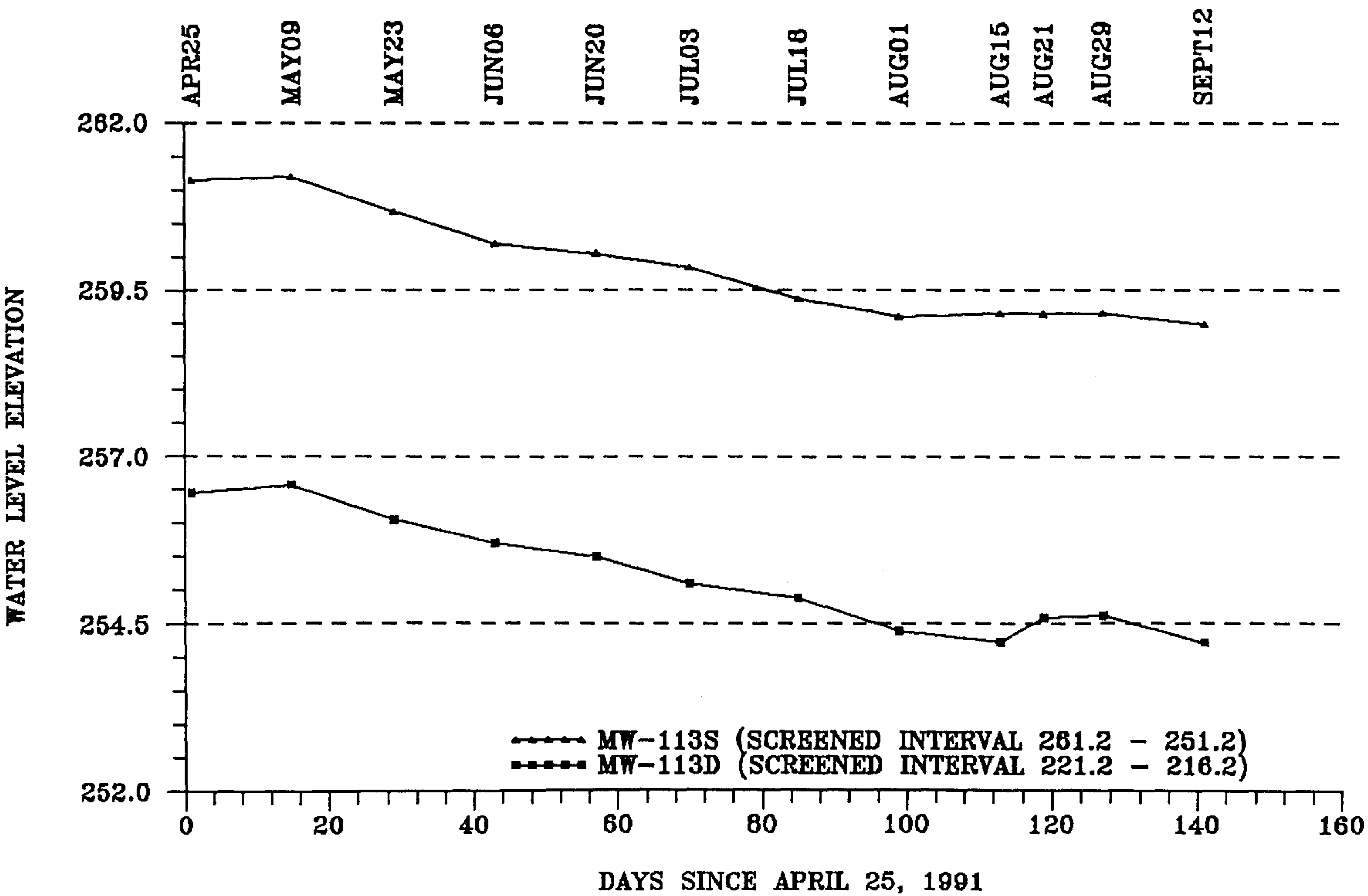
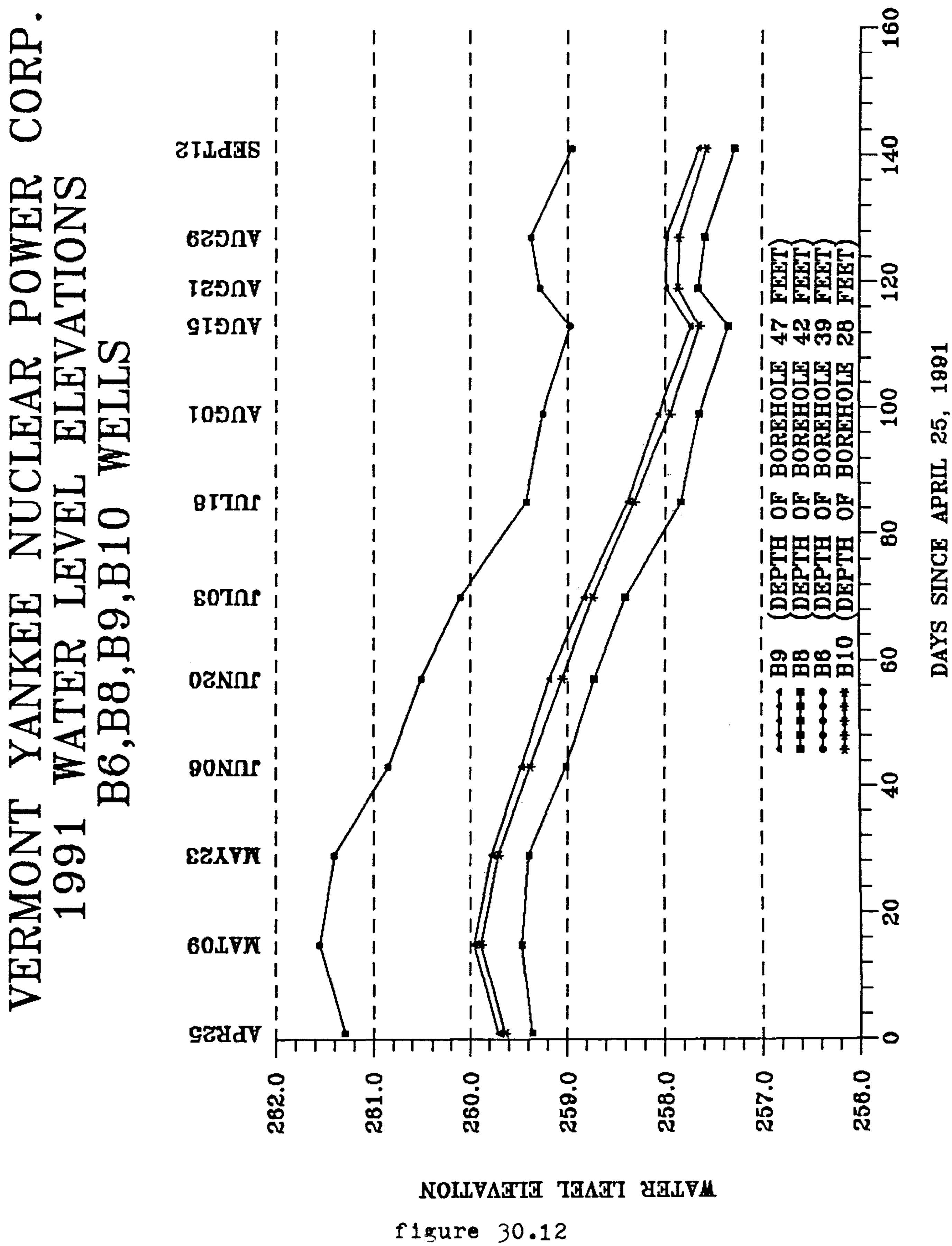


figure 30.11



VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
B6,B8,B9,B10 WELLS
APR25
MAY09
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
262.0
261.0
260.0
259.0
258.0
257.0
256.0
WATER LEVEL ELEVATION
0
20
40
60
80
100
120
140
160
DAYS SINCE APRIL 25, 1991
B9 (DEPTH OF BOREHOLE 47 FEET)
B8 (DEPTH OF BOREHOLE 42 FEET)
B6 (DEPTH OF BOREHOLE 39 FEET)
B10 (DEPTH OF BOREHOLE 28 FEET)

figure 30.12

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
106,113S,111 WELLS

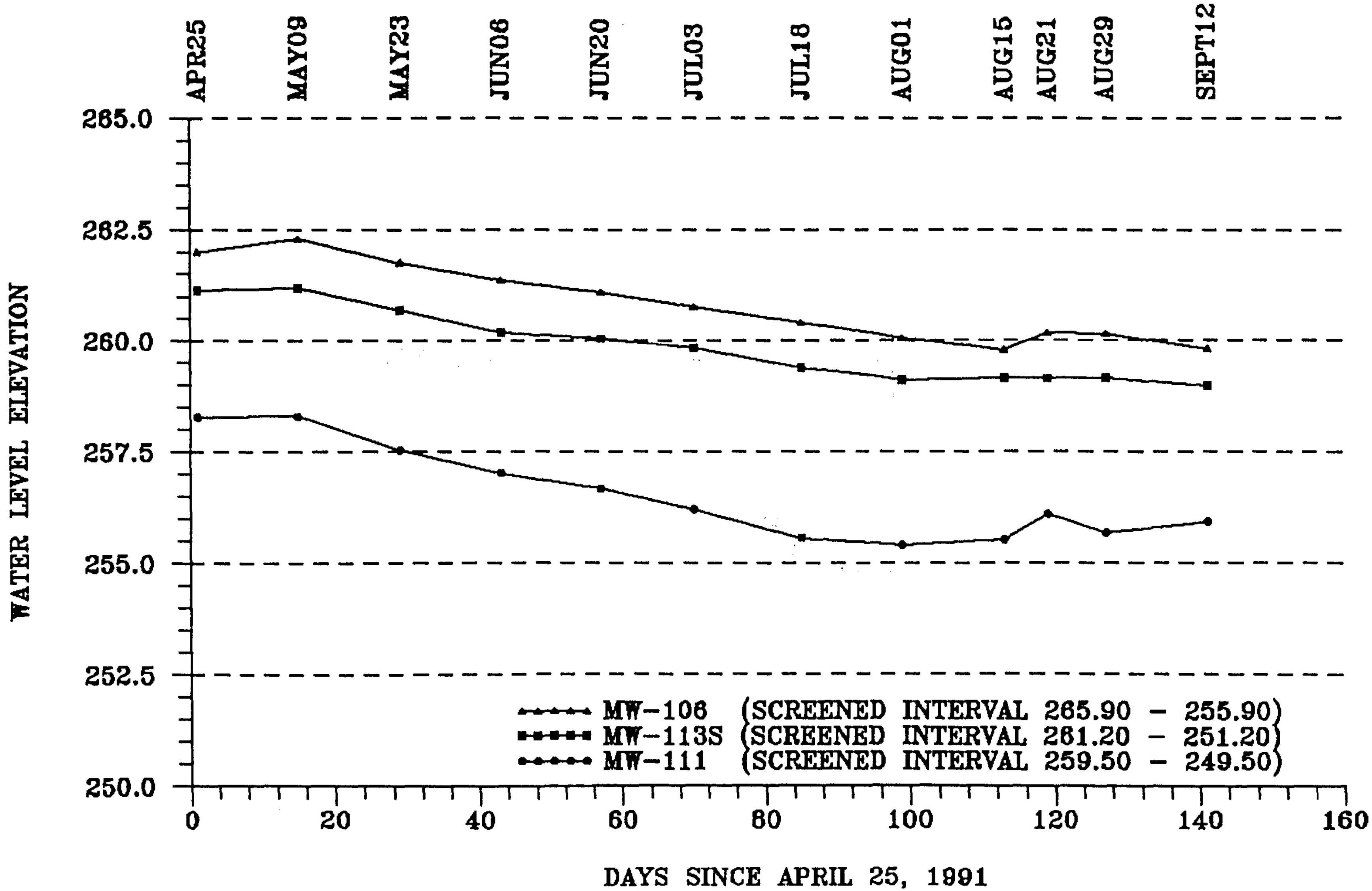


figure 30.13

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
109,110,102 WELLS

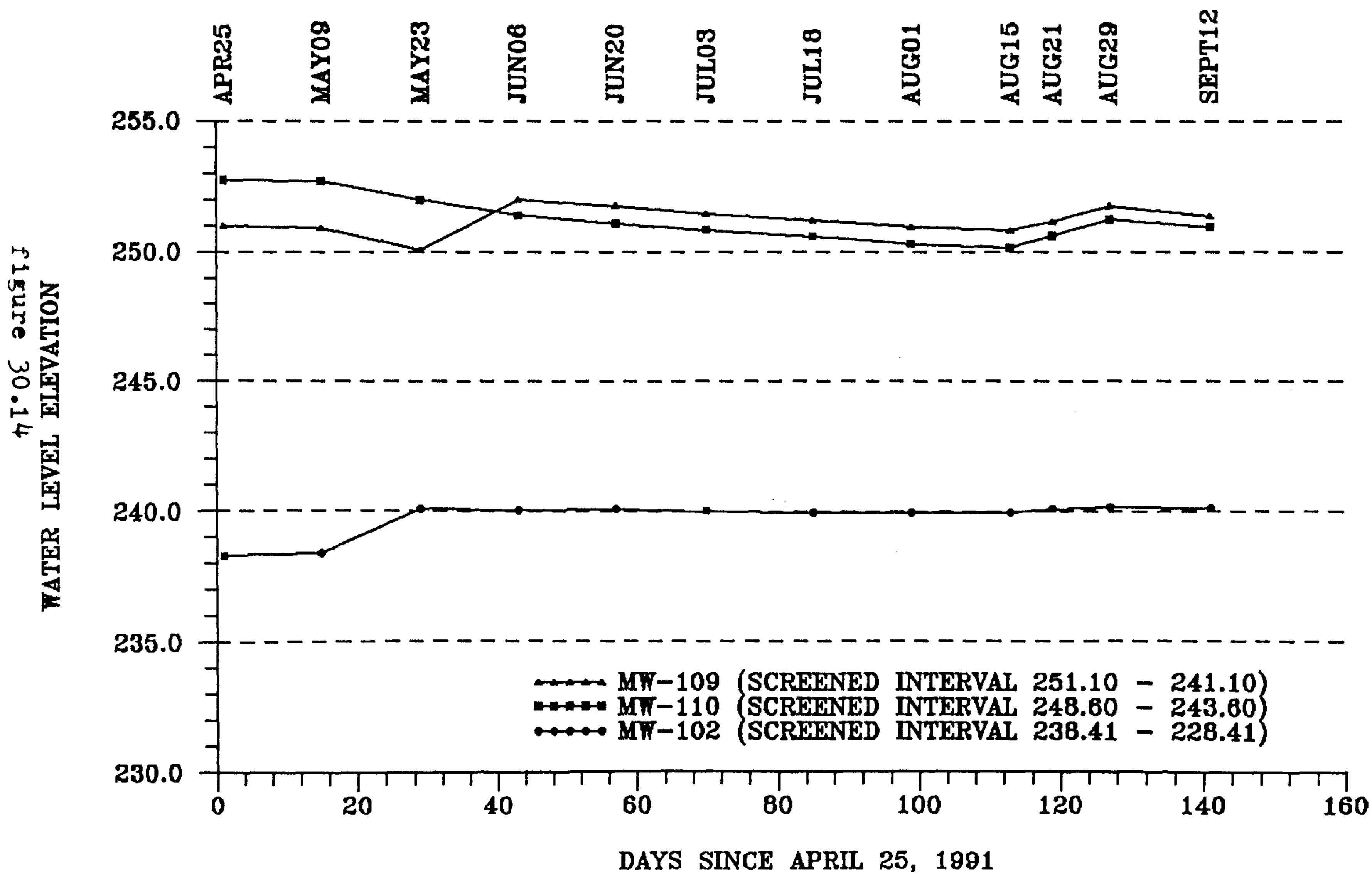


figure 30.14

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
214,215,216,217 WELLS

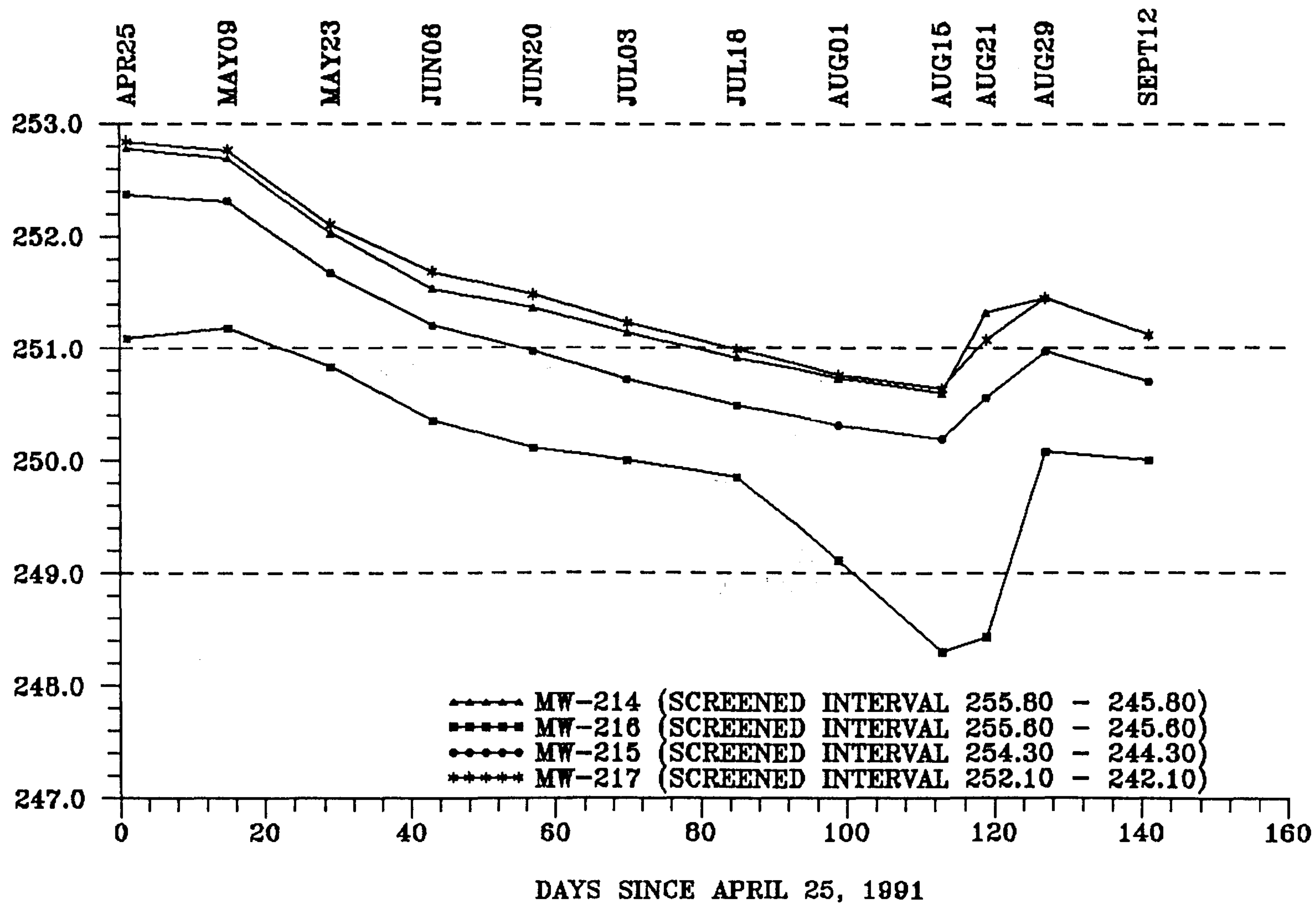


figure 30.15

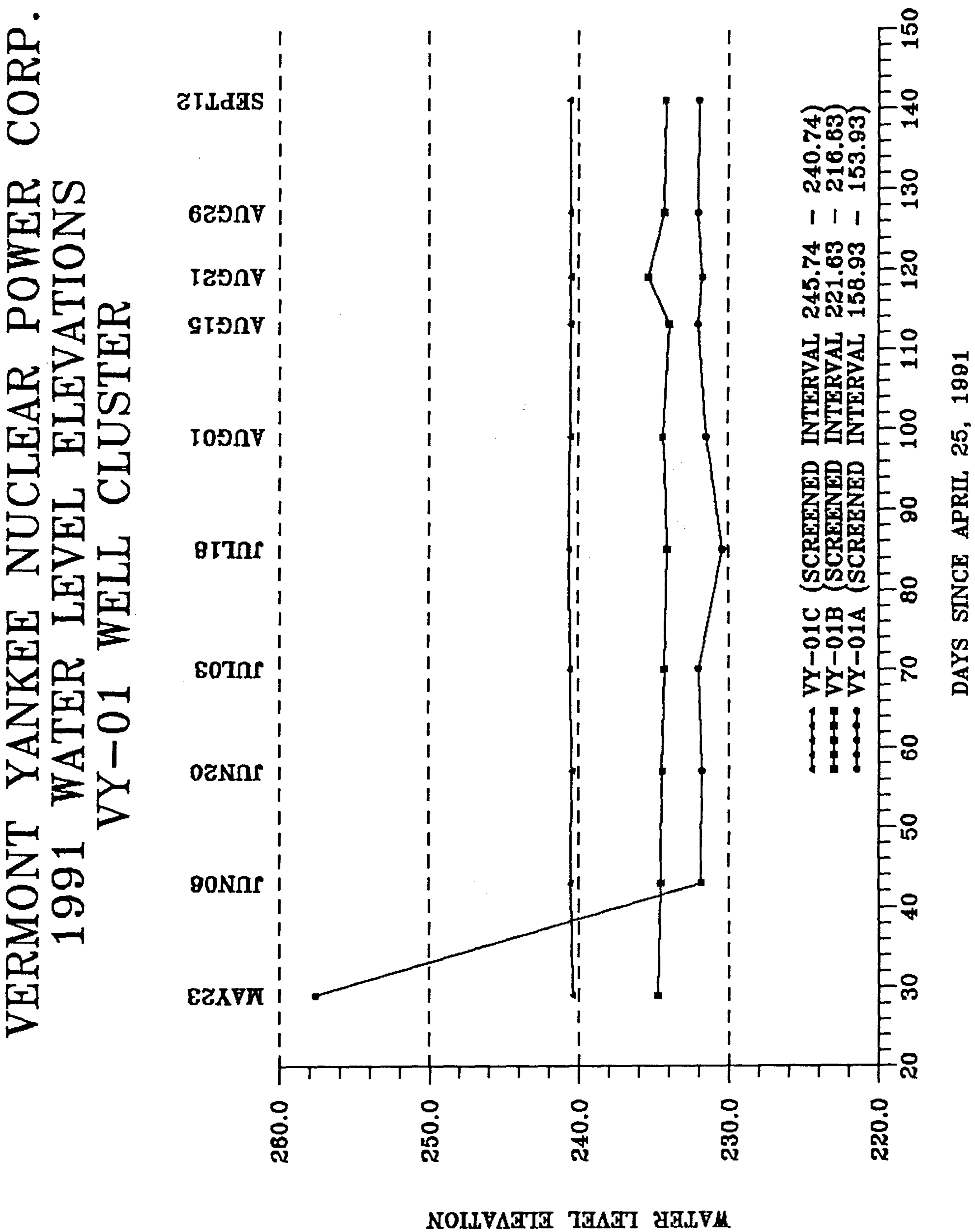

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
VY-01 WELL CLUSTER
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
VY-01C (SCREENED INTERVAL 245.74 - 240.74)
VY-01B (SCREENED INTERVAL 221.63 - 216.63)
VY-01A (SCREENED INTERVAL 158.93 - 153.93)
DAYS SINCE APRIL 25, 1991
WATER LEVEL ELEVATION
280.0
250.0
240.0
230.0
220.0
20
30
40
50
60
70
80
90
100
110
120
130
140
150

figure 30.16

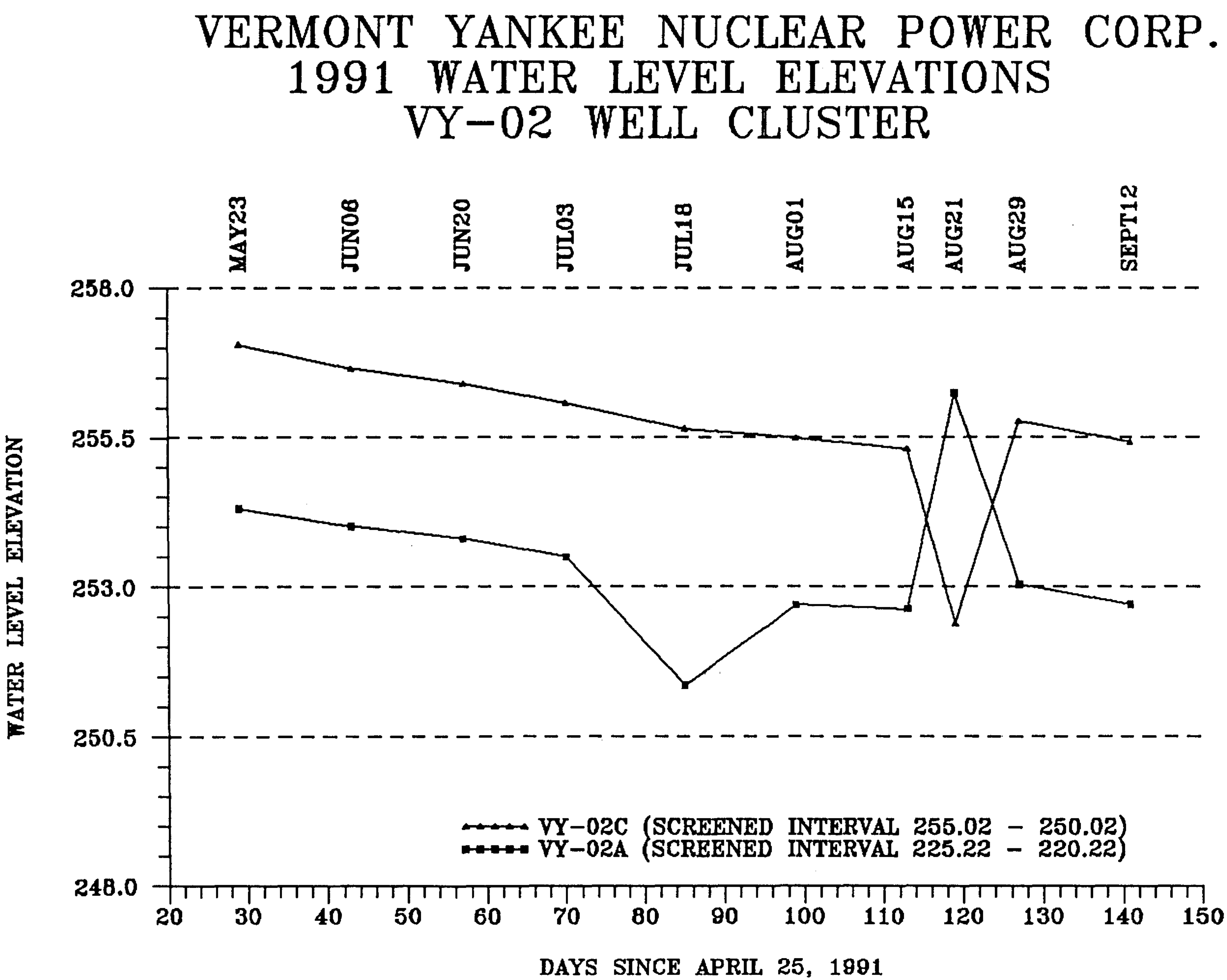

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
VY-02 WELL CLUSTER
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
WATER LEVEL ELEVATION
258.0
255.5
253.0
250.5
248.0
VY-02C (SCREENED INTERVAL 255.02 - 250.02)
VY-02A (SCREENED INTERVAL 225.22 - 220.22)
20
30
40
50
60
70
80
90
100
110
120
130
140
150
DAYS SINCE APRIL 25, 1991

figure 30.17

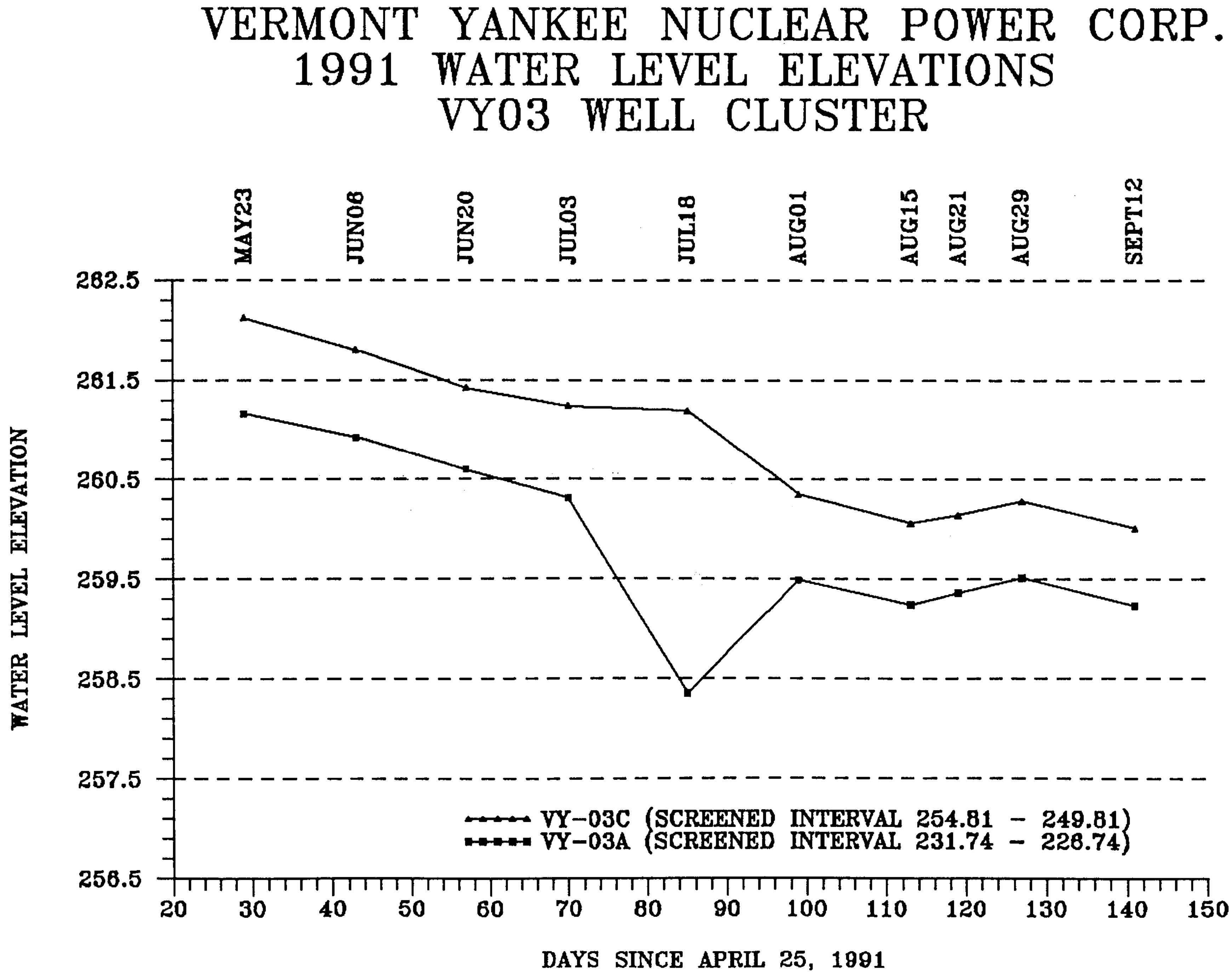

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
VY03 WELL CLUSTER
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
WATER LEVEL ELEVATION
262.5
261.5
260.5
259.5
258.5
257.5
256.5
VY-03C (SCREENED INTERVAL 254.81 - 249.81)
VY-03A (SCREENED INTERVAL 231.74 - 228.74)
20
30
40
50
60
70
80
90
100
110
120
130
140
150
DAYS SINCE APRIL 25, 1991

figure 30.18

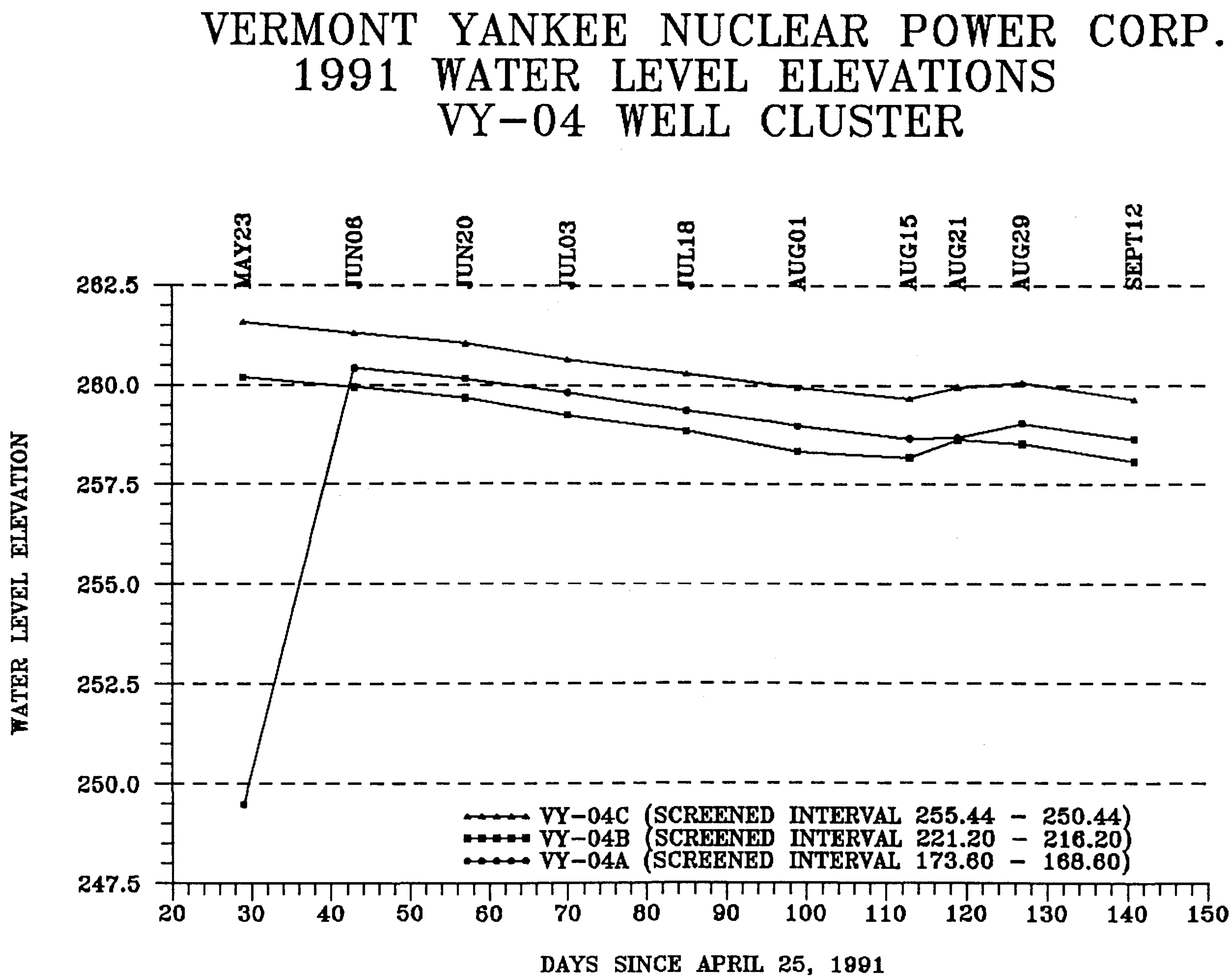

VERMONT YANKEE NUCLEAR POWER CORP.
1991 WATER LEVEL ELEVATIONS
VY-04 WELL CLUSTER
MAY23
JUN06
JUN20
JUL03
JUL18
AUG01
AUG15
AUG21
AUG29
SEPT12
WATER LEVEL ELEVATION
262.5
260.0
257.5
255.0
252.5
250.0
247.5
20 30 40 50 60 70 80 90 100 110 120 130 140 150
DAYS SINCE APRIL 25, 1991
VY-04C (SCREENED INTERVAL 255.44 - 250.44)
VY-04B (SCREENED INTERVAL 221.20 - 216.20)
VY-04A (SCREENED INTERVAL 173.60 - 168.60)

figure 30.19

SHALLOW UNCONSOLIDATED POTENTIOMETRIC SURFACE

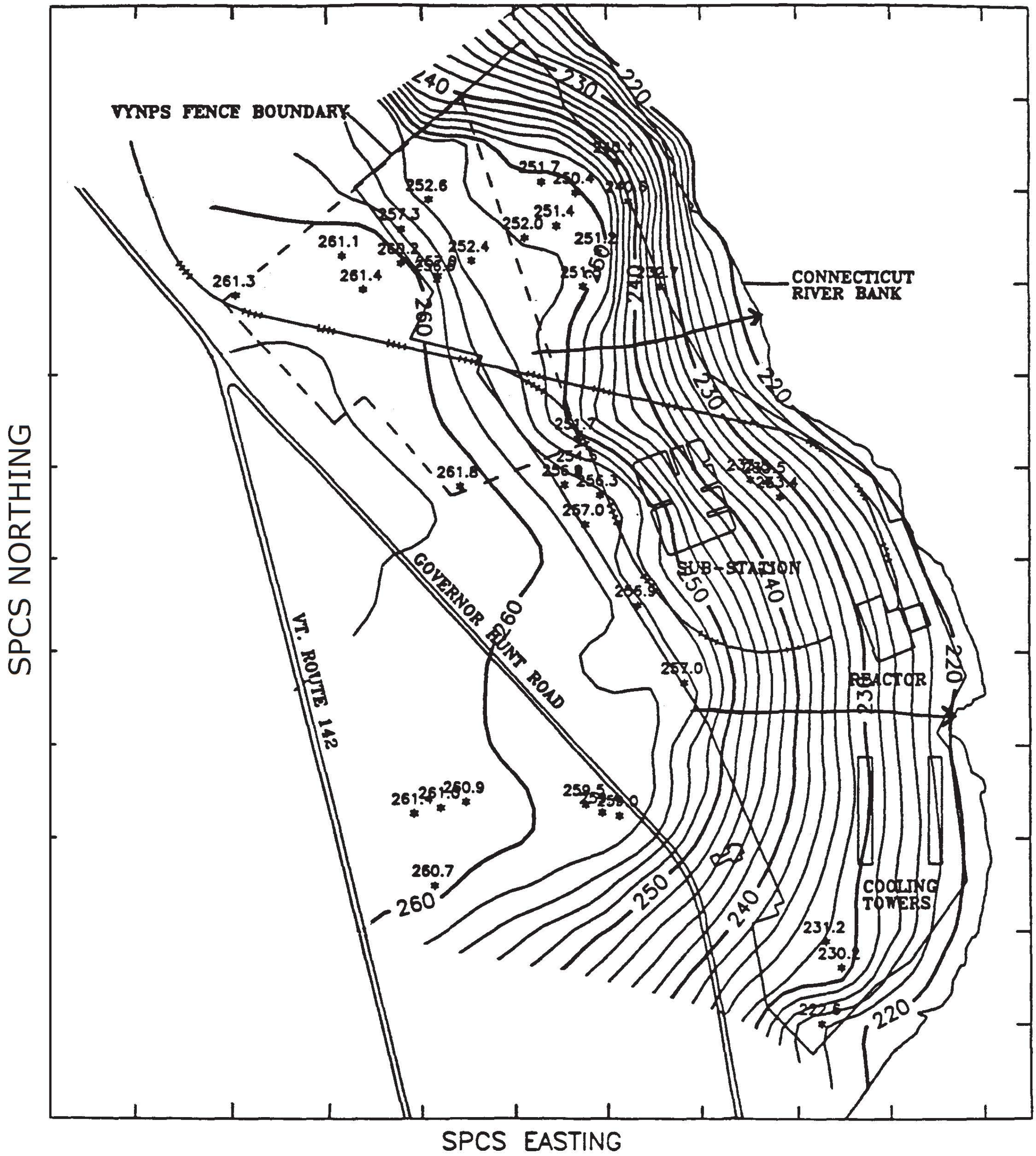


figure 31

much of the site, but then drops sharply at the river bank. The steepness of the gradient in the northern portion of the site relative to the southern portion of the site, may reflect the greater steepness of the stream bank in the north relative to the south. The intermediate unconsolidated sediment potentiometric surface shows flow towards the river (see figure 32). The potentiometric surface for the deep bedrock is very similar to that of the shallow and intermediate potentiometric surfaces (see figure 33). Water flows towards the Connecticut River. The shallow-bedrock head difference and shallow-intermediate head difference generally increases moving east towards the river, but then declines to disappear upon meeting the river (see figure 34A, 34B). This is due to the topography of the stream bank and the relative thickness of consolidated sediments and increasing depth of bedrock, nearer the stream.

Hydrologic cross-sections confirm the above description (see figure 35). Cross-section B-B' describes the northern part of the site (see figure 36). This cross-section shows flow towards the Connecticut River, and a shallow-bedrock head difference which increases near the river bank. A source of temporary debate was the possibility of a ground water divide located at well 107. Early data indicated a divide but subsequent revised data indicated no divide was present. The influence of the topographic high under VY-02 was considered the reason for any possible groundwater divide. Cross-section C-C' shows the southern part of the site (see figure 37). Flow is again towards the river. Cross-section D-D' shows a north-south view. Cross section E-E' shows flow to the west of the site, with water gradually flowing to the river, the gradient being less steep due to the relative distance from the river (see figure 38). Depth to water table varies from 3 - 18 feet over the site, and possibly over 30 in southern portion (see figure 39). Depth increases near the stream bank to 12-14 feet, as the water table falls away from the land surface, but then meets the land surface at the river. From water level measurements taken on June 6, 1991, the unsaturated zone ranges in thickness from

INTERMEDIATE UNCONSOLIDATED POTENTIOMETRIC SURFACE

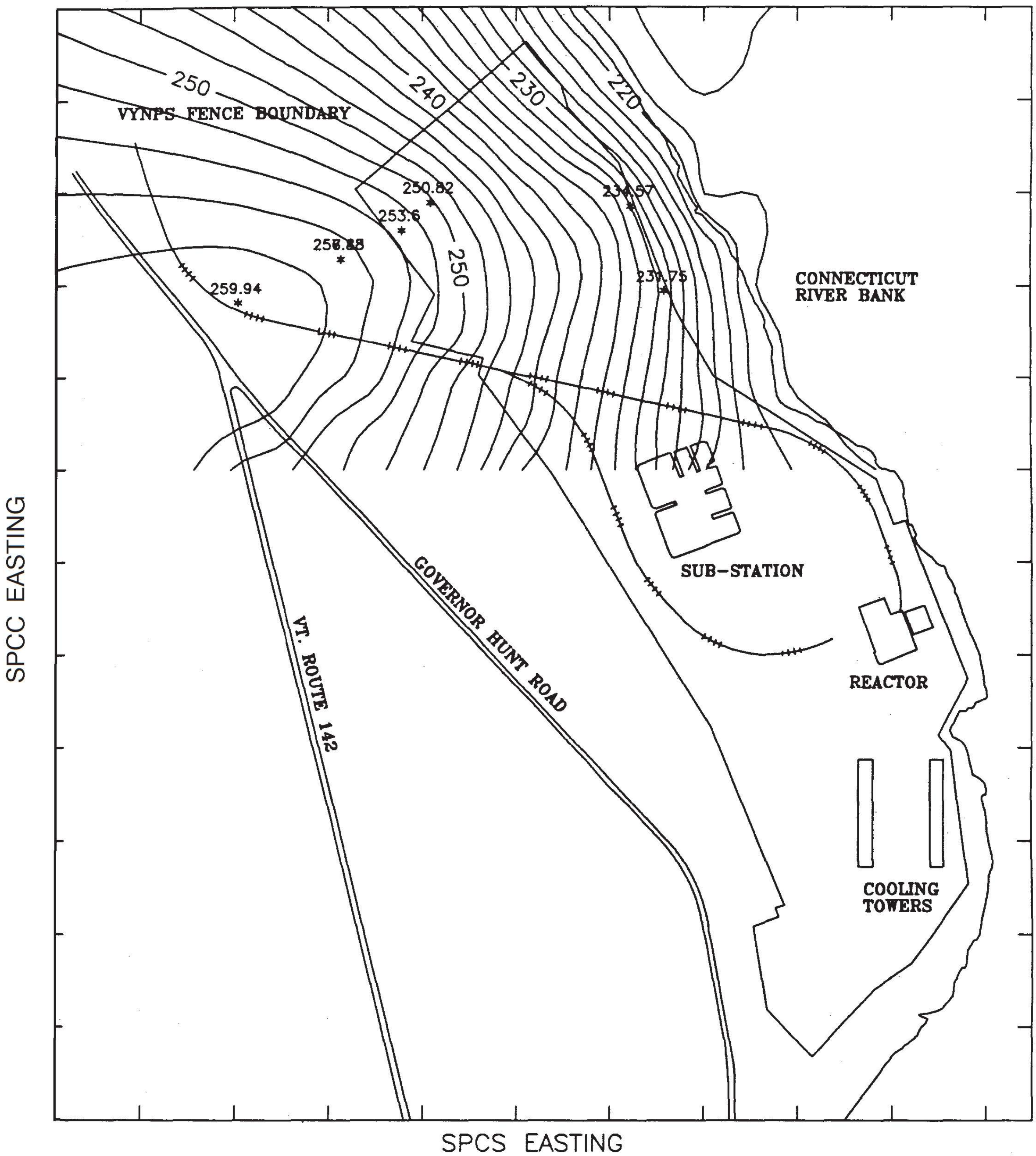


figure 32

BEDROCK & DEEP UNCONSOLIDATED POTENTIOMETRIC SURFACE

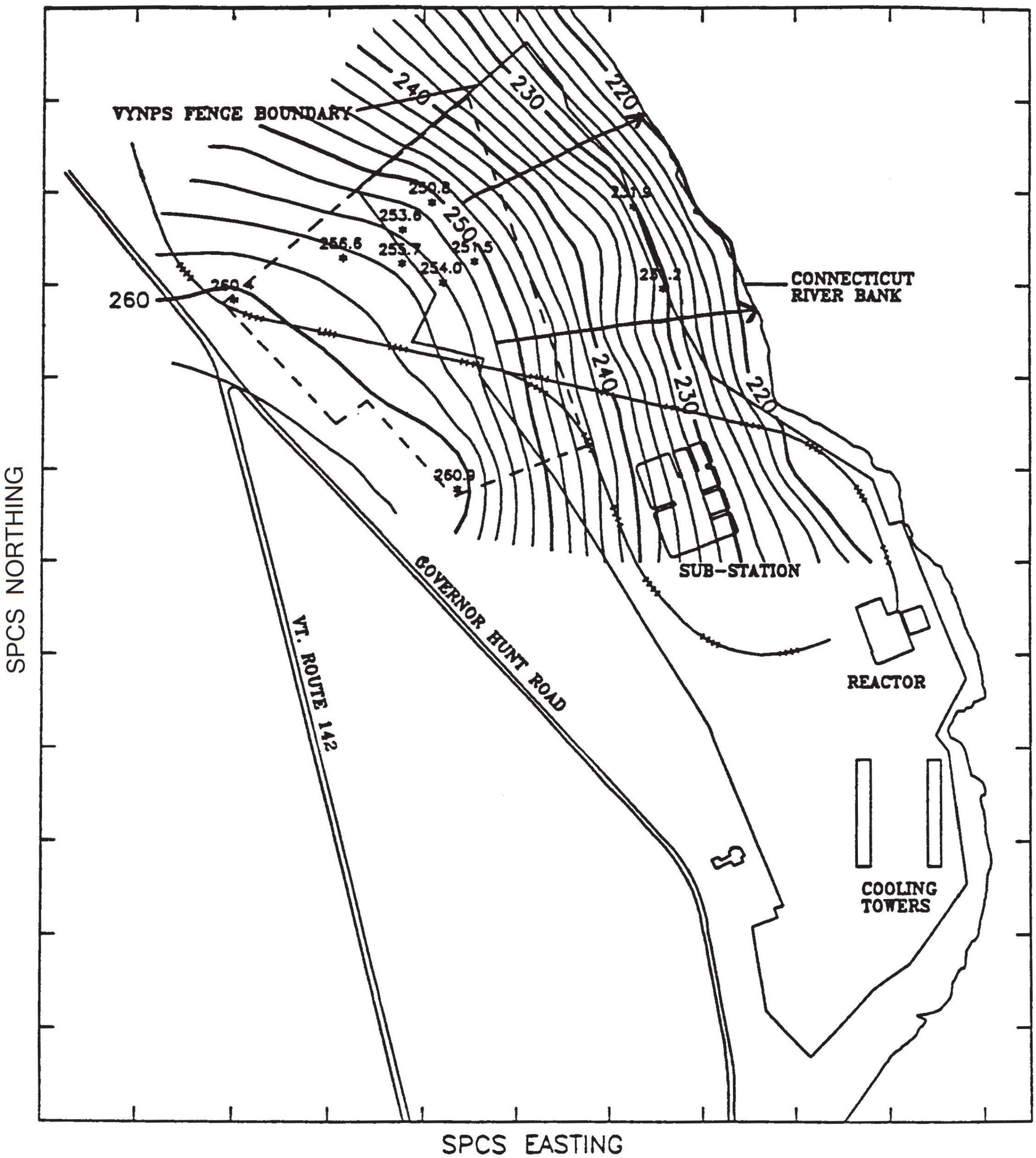


figure 33

SHALLOW/BEDROCK HEAD DIFFERENCE

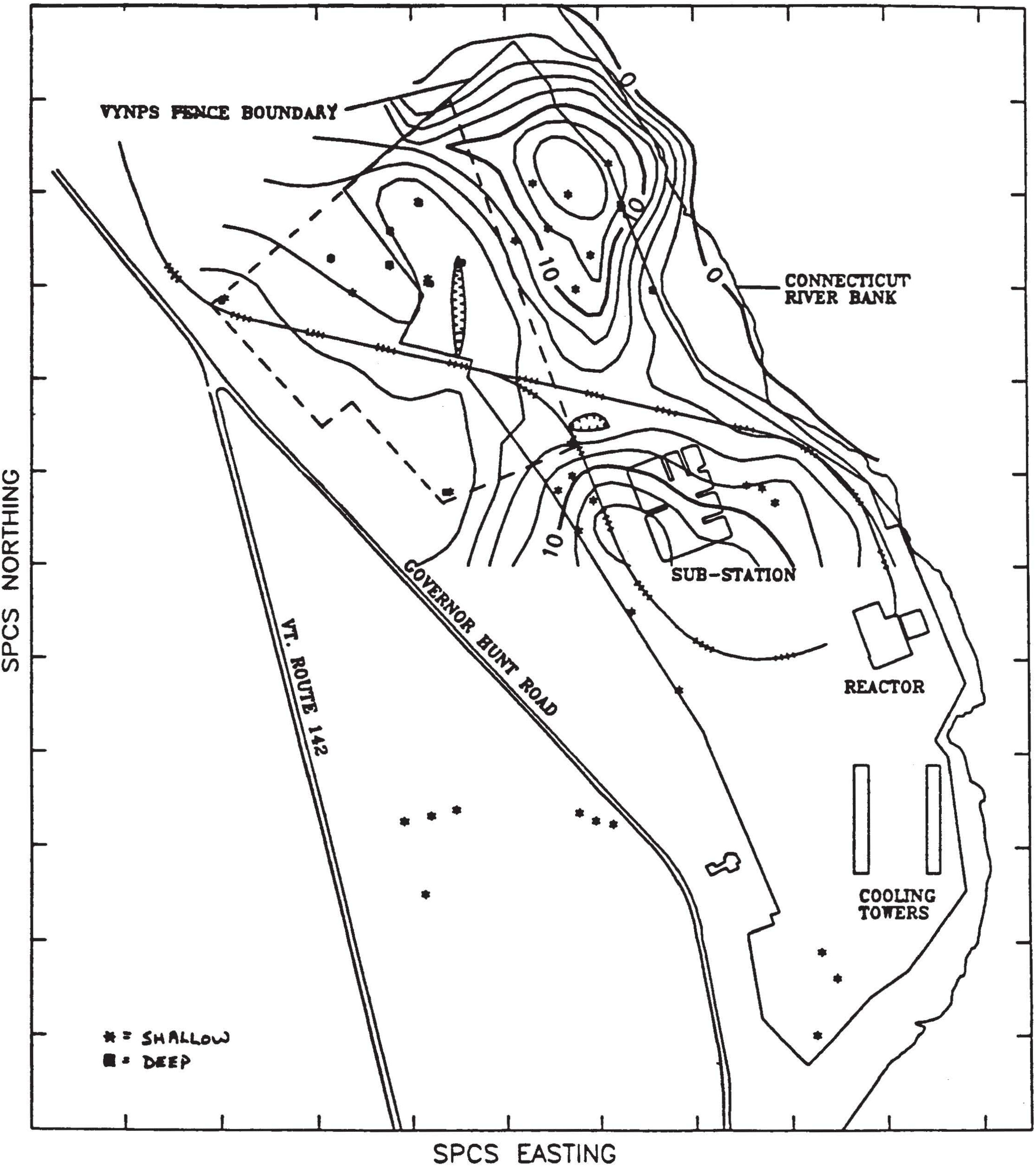


figure 34A

SHALLOW/INTERMEDIATE HEAD DIFFERENCE

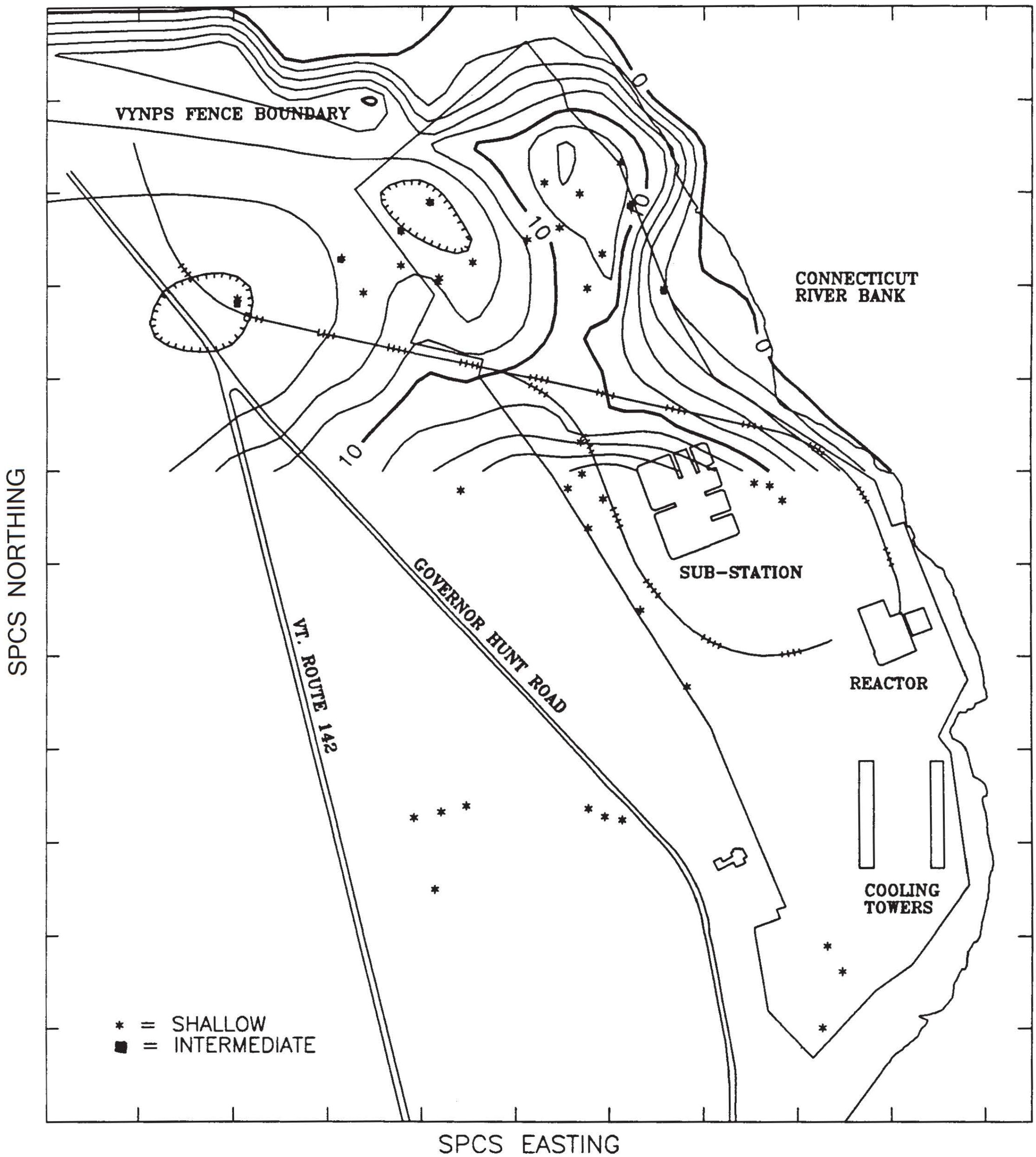


figure 34B

Hydrogeologic Cross Sections

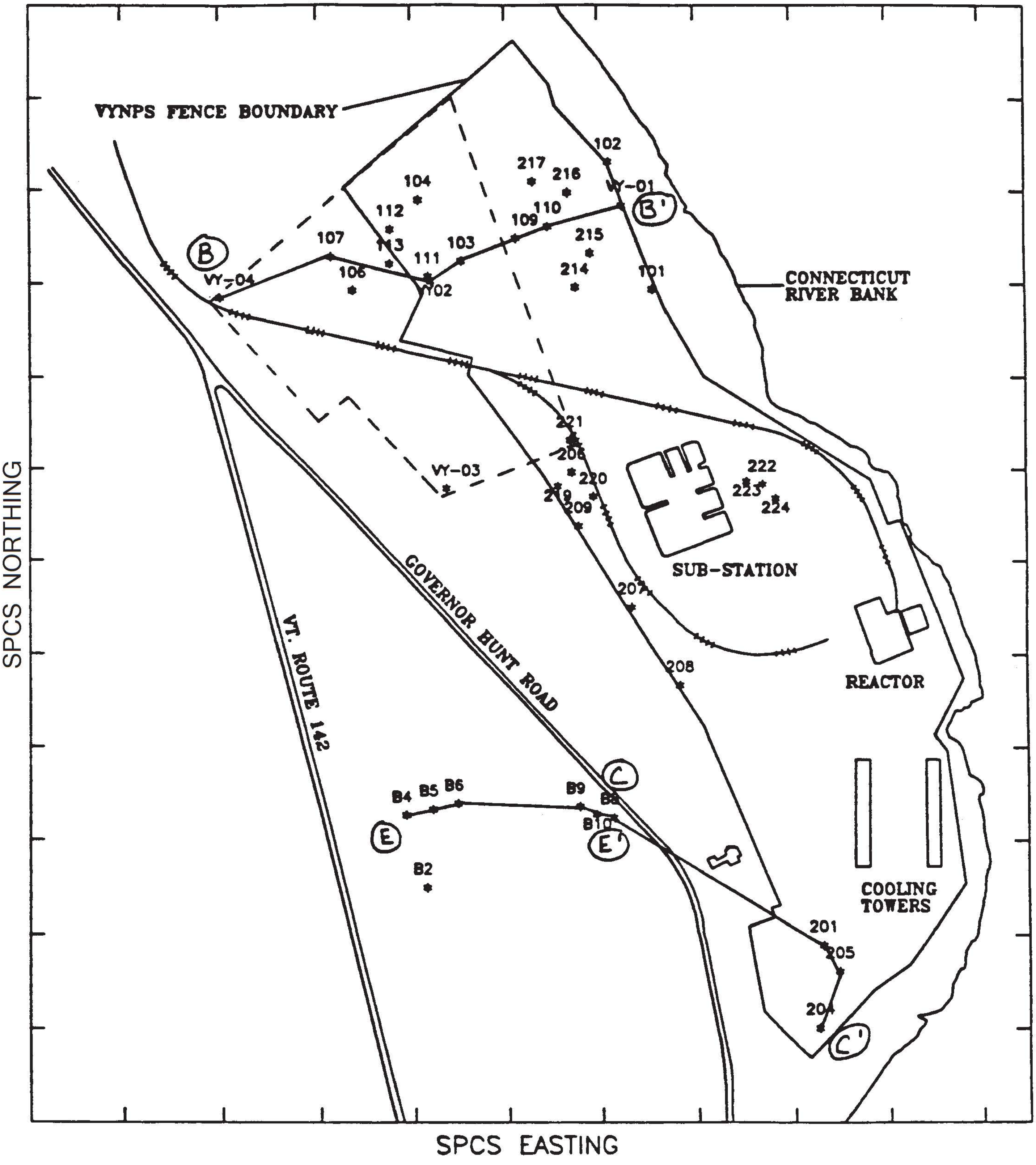
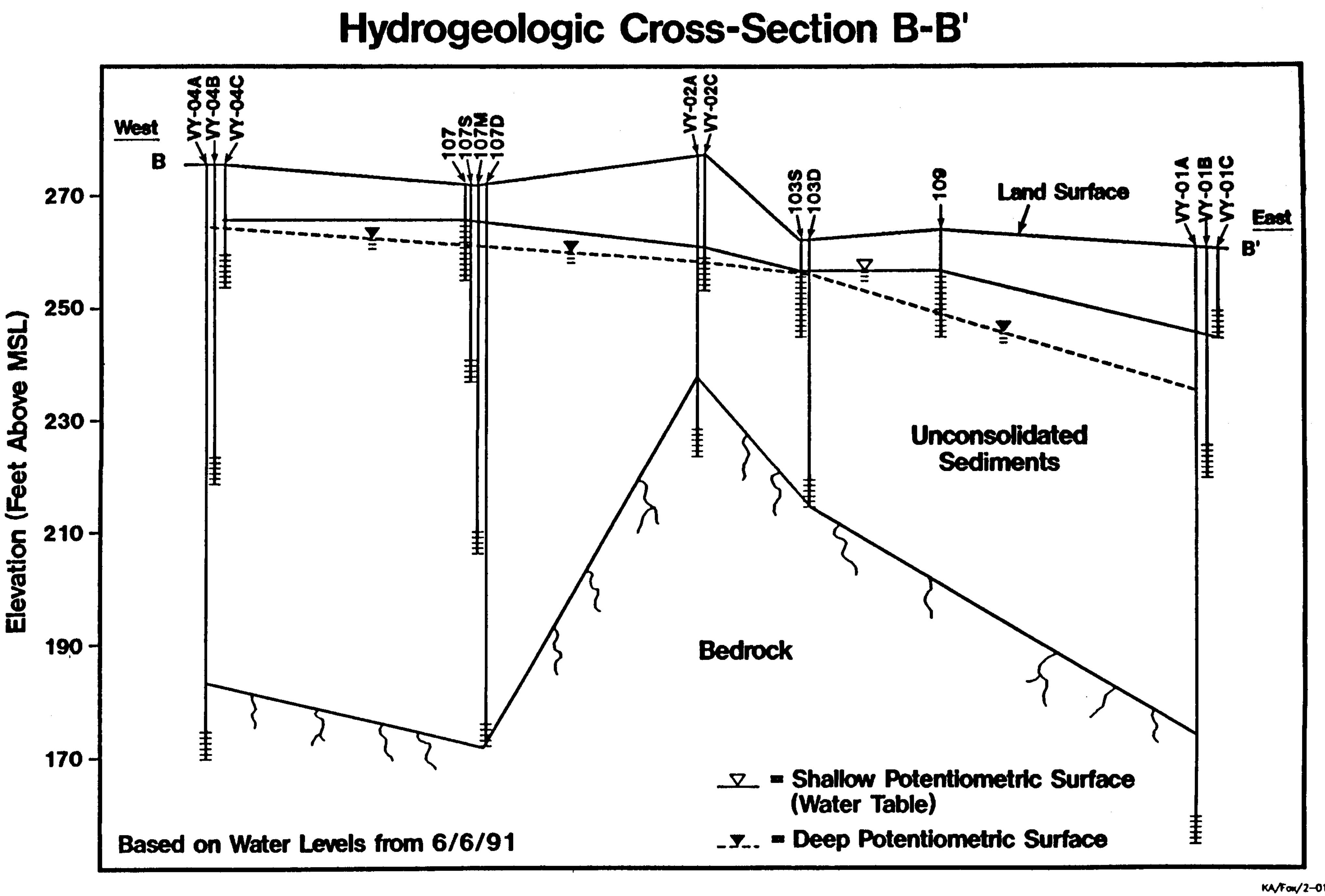


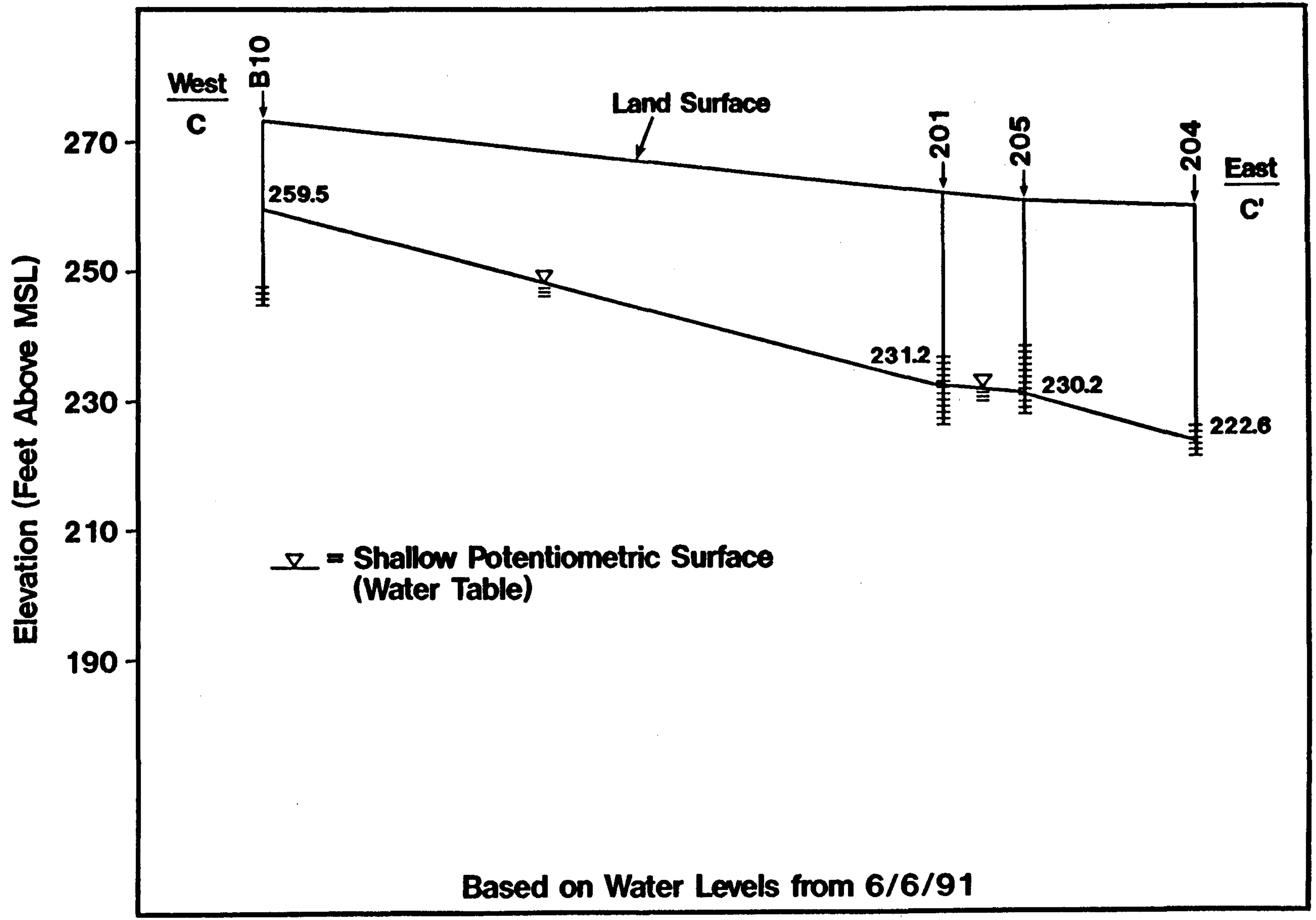
figure 35



Hydrogeologic Cross-Section B-B'
West
B
VY-04A
VY-04B
VY-04C
107
107S
107M
107D
VY-02A
VY-02C
103S
103D
109
Land Surface
VY-01A
VY-01B
VY-01C
East
B'
Elevation (Feet Above MSL)
270
250
230
210
190
170
Unconsolidated Sediments
Bedrock
= Shallow Potentiometric Surface (Water Table)
= Deep Potentiometric Surface
Based on Water Levels from 6/6/91
KA/Fox/2-01

figure 36

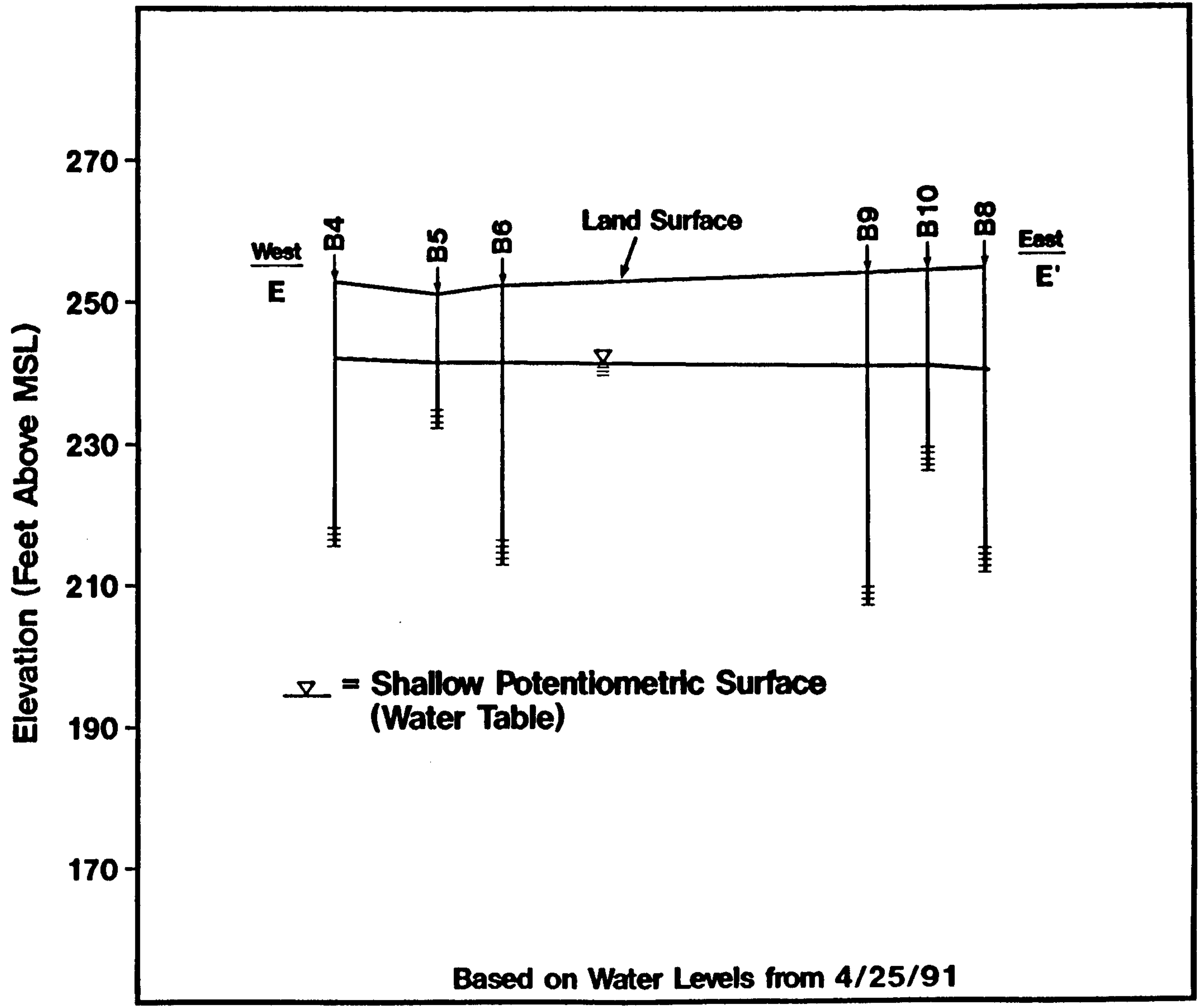
Hydrogeologic Cross-Section C-C'



KA/Fox/2-02

figure 37

Hydrogeologic Cross-Section E-E'



KA/Fox/2-04

figure 38

MINIMUM DEPTH TO WATER TABLE (SPRING 91)

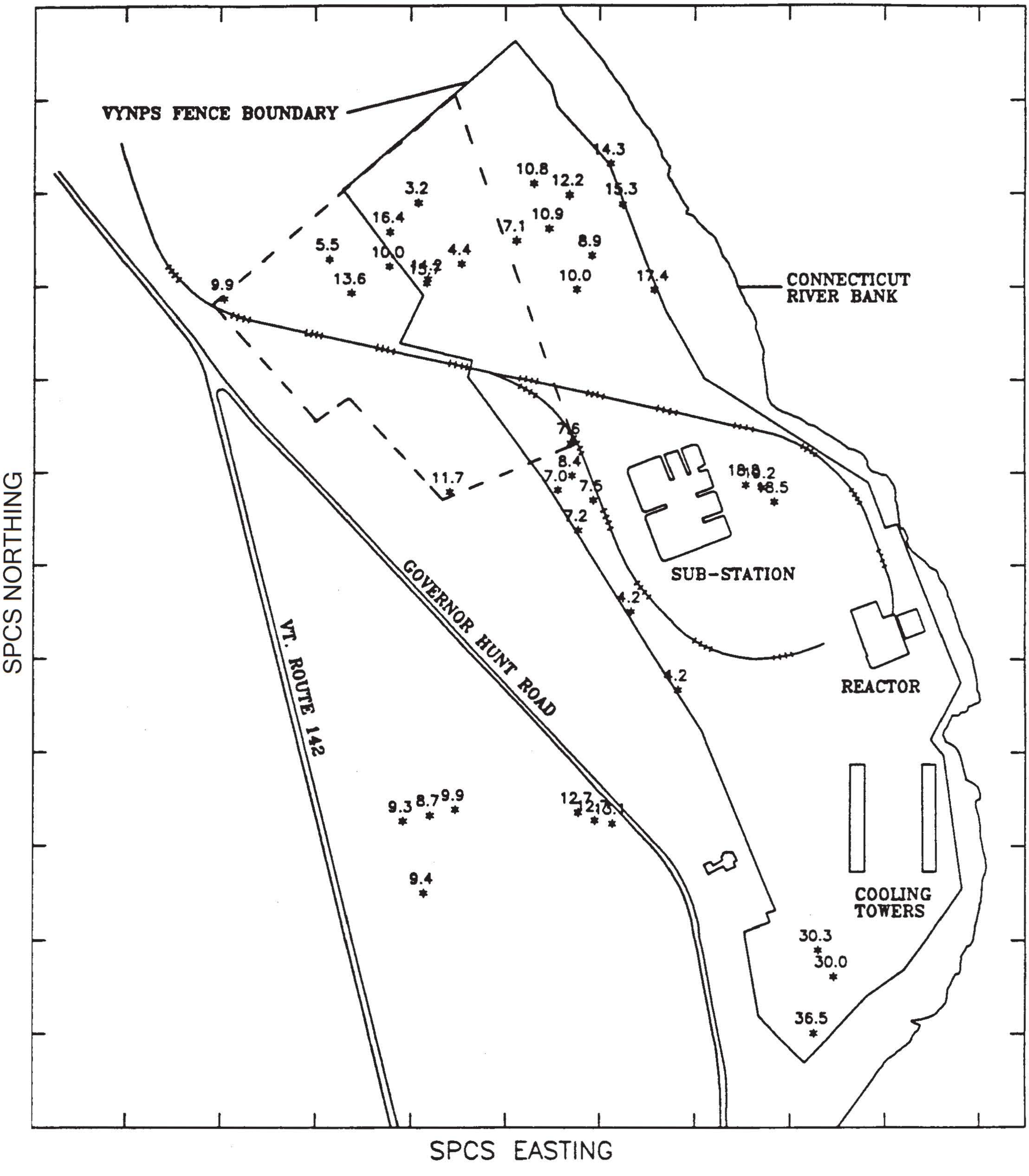
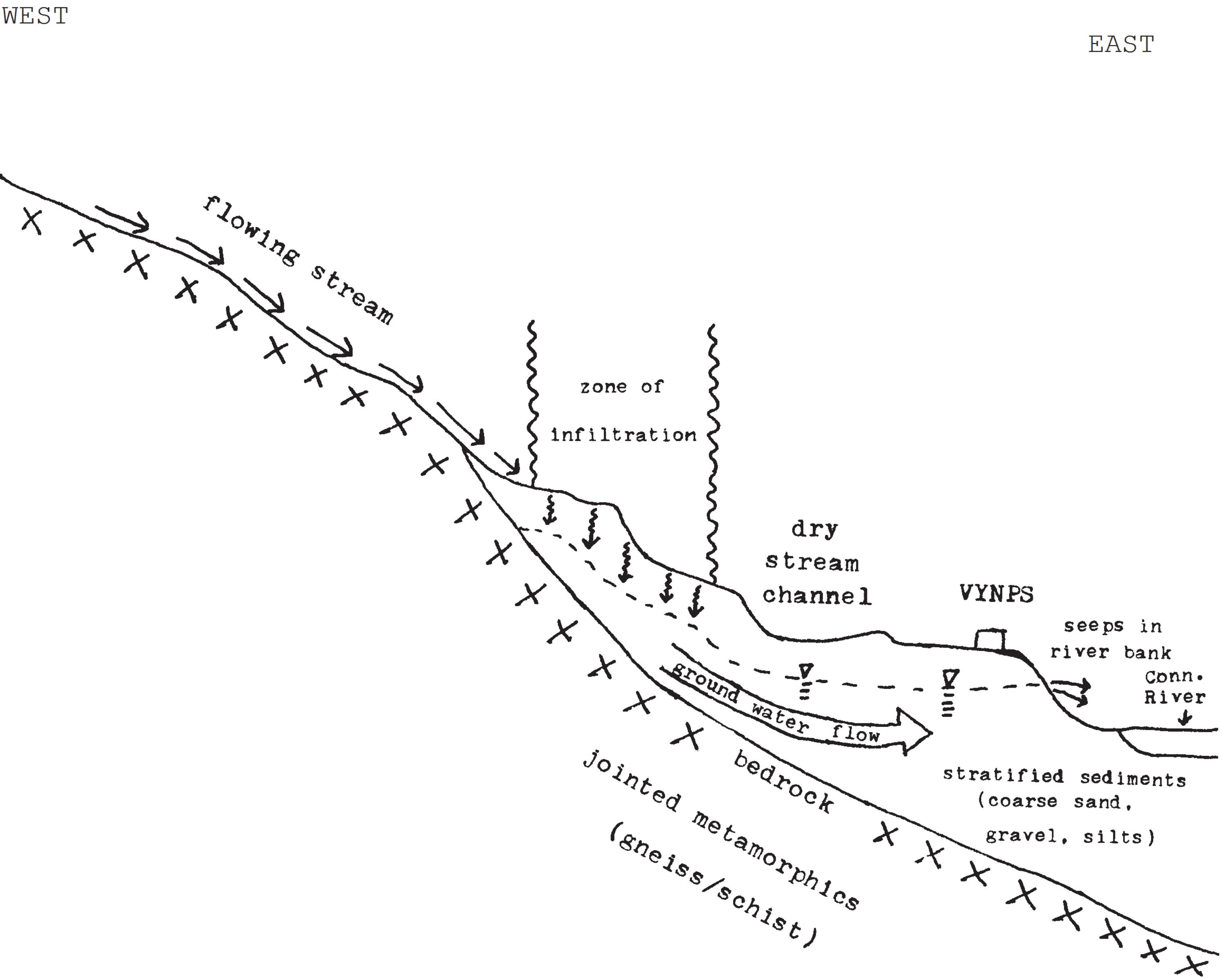


figure 39A

4.22 to 30.33 feet. Much of this variation in depth to groundwater is a reflection of topography with a thick unsaturated zone in areas of higher elevation and a thinner unsaturated zone in areas of lower elevation. Depth to groundwater is also seasonal, with minimum depth occurring in winter and spring due to large amounts of precipitation and low evapotranspiration and maximum thickness occurring in summer and early fall due to low amounts of precipitation, high temperatures and evapotranspiration.

From an onsite visit, from July 1-3 1991 a conception of groundwater flow was made by WHN and Battelle (see figure 40). On the topographic highs, water was observed to flow in streams. The streams were cut into bedrock, and flowing directly on the bedrock with little or no sediment on the stream bed. A stream (Roaring Brook?) off Tyler Hill Road was measured at 0.63 gallons per second. Flow in this stream continued where it merged with another stream then disappeared before reaching the road, infiltrating into sediment along the stream bed which became more prominent with lower altitude. A gravel pit near the stream was studied. It showed stratified deposits varying from fine silt to cobble layers. This is most likely a kame, kame terrace or the topset beds of a delta. These deposits are very similar to those that underlie the site. A stream to the west of the Miller Farm, was found to be dry along its path. The stream bed was very sandy and gravelly. This stream bed continued east until reaching the base of the topographic highs and then bifurcated north and south. Two ponds are present in the north-south parts of the stream. These ponds are stagnant but could flow either north or south to streams which drain to the river if there was heavy precipitation or runoff from the topographic highs. Dry stream channels continue to the Connecticut River, indicating flow sometimes occurs. During high flow times, the zone of infiltration would likely extend to the Connecticut River. A small gravel pit was located on the Miller Farm. It showed sandy, gravelly deposits. Three seeps along the river bank north from the VY01 cluster were measured (see figure



Schematic Flow Diagram

*note: not to scale

figure 40

41). Seep #1 yielded 0.70 cups per second, seep #2 yielded 0.19 cups per second, and seep #3 yielded 0.11 cups per second.

In summary, surface water flows in streams down the topographic highs on or near the bedrock surface, and acts as a source of recharge. As the streams flow out onto alluvial deposits, water infiltrates/percolates downward through stratified alluvial outwash deposits until the stream beds are eventually dry. The water then continues to flow towards the river as groundwater and either enters the river below the land surface or emerges as seeps. Equipotential maps made from water level measurements collected by WHN (1991) during 1991 from spring to fall from piezometers on the site confirm flow of groundwater to the Connecticut River. Fracture traces and small faults may alter the flow pattern.

VI. Conclusion

There are two key favorable conditions for the site. First, the proposed waste repository would be located on the site of the Vermont Yankee Nuclear Power Plant. Second, the large effective porosity of the unconsolidated sediments under the site would tend to slow contaminate migration. However, there are numerous disadvantages. There was a very short distance to the Connecticut River. Though a large river is an excellent source of dilution, large numbers of production wells are located along the river. The hydraulic conductivity of the sediments was very high, meaning relatively fast travel times. There was low depth to groundwater. Also, the bedrock in the area is highly fractured and jointed, leading to the possibility of contaminants moving in unknown directions. Thus the technical staff of the NRC noted that "from the view of groundwater flow and transport, this site appears to have limited natural attributes for waste isolation." A consultant for the Vermont Department of Public Service stated that "In my opinion, the VYNPS does not appear to have any redeeming hydrogeologic qualities. . .(and) it does not make sense to spend a lot of time and

SEEP LOCATIONS

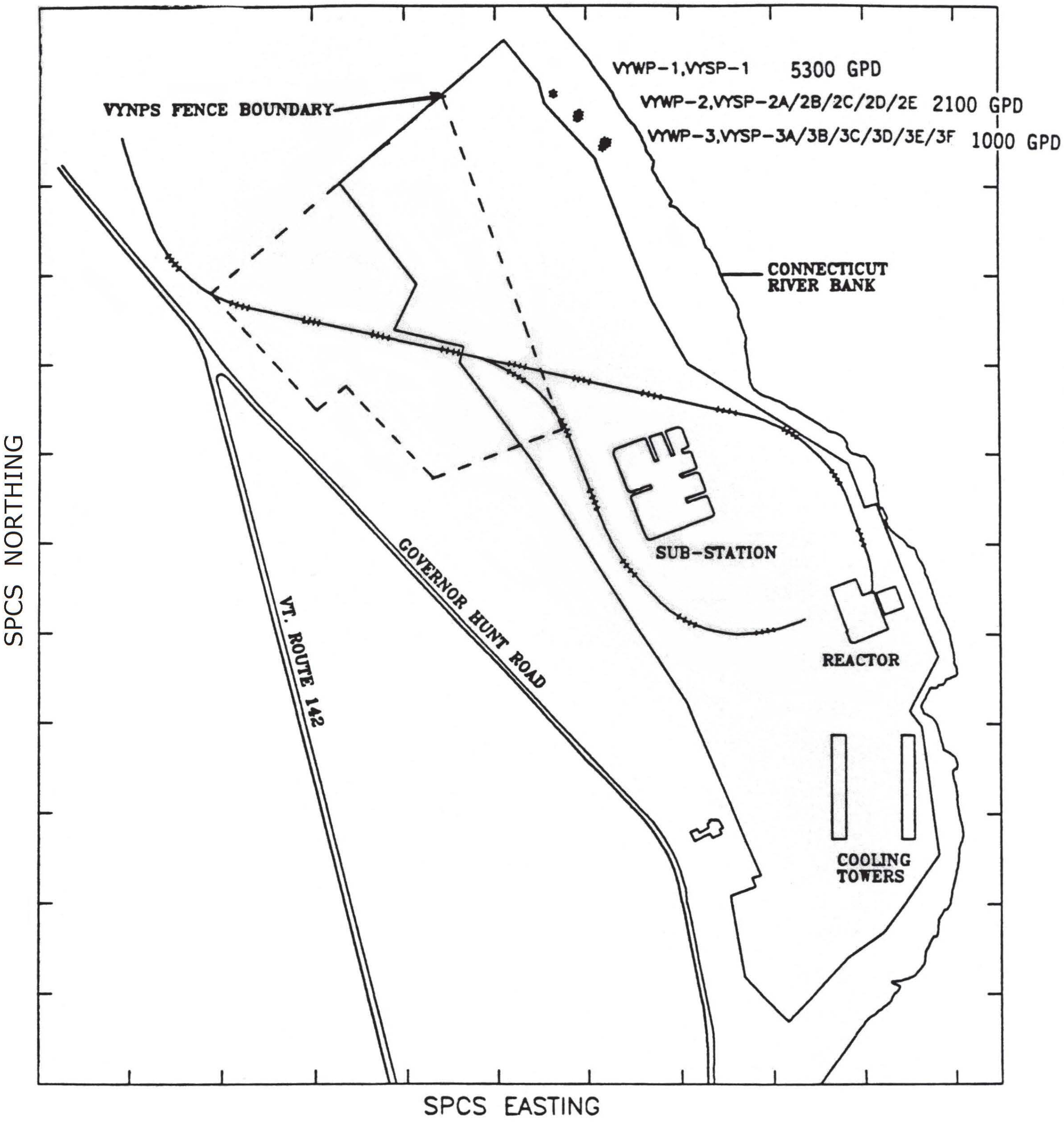


Figure 41

money fully characterizing a site which does not appear to provide some degree of natural protection." Since further technical tests were deemed by consultants unlikely to yield results significantly different from those already found, the Authority terminated all characterization activities. Despite these faults, the site was also nixed due to location of two small wetland areas on the site proper. According the Vermont regulations, these wetlands are protected and construction was prohibited.

Sources of Figures

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3. Ibid.
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6. Ibid., p. 13.
7. Ibid., p. 63.
7A. Ibid., fold out map.
8. Ibid., p. 90.
9. Ibid., p. 118.
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12. Ibid., p. 137.
13A. Ibid., p. 151-2.
13B. Ibid., p. 152-3.
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17. Ibid., p. 209.
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29. Ibid.
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30.1-30.19. Ibid.
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3. Hepburn, Trask, Rosenfeld, and Thompson Bedrock Geology of the Brattleboro Quadrangle, Vermont-New Hampshire: Bulletin No. 32, (Montpelier Vermont, Agency of Environmental Conservation and the Department of Water Resources and Environmental Engineering, 1984).

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